ARCTIC CLOUD COVER DURING THE SUMMERS OF 1977-1979

David A. Robinson, George J. Kukla and Mark C. Serreze

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
OF
COLUMBIA UNIVERSITY

Palisades, New York 10964

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ABSTRACT

Cloud cover in the Arctic Basin has been charted from satellite images at approximately 3 day intervals for the months of May to August from 1977 to 1979. Three classes of cloud thickness at three altitudes were mapped and digitized together with sea level pressure.

Cloudiness was found to be heterogeneous in space and time. Optically thick clouds had high tops and were associated with low pressure systems and airmasses advected from the south. Clouds of moderate thickness were the most prevalent. Cloud-free skies were most often colocated with high pressure. The central Arctic was cloudiest, whereas the Canadian Archipelago was least cloudy. Overall, thick clouds were considerably less common than in earlier analyses drawn from ground and drifting station data. Cloud-free episodes throughout the basin persisted long enough to significantly affect the surface radiation budget and the dissipation of snow and ice.

Our results indicate that climate models which attempt to assess the impact of CO_2 on the radiation budget in the high latitudes should take into account the heterogeneity of cloud extent, thickness and height in the Arctic Basin.

1. INTRODUCTION

Numerical climate models predict the largest changes from increased CO_2 to occur in the high latitudes. Specifically, it is expected that arctic snow and sea ice will melt earlier in summer and start growing later in fall, consequently becoming less thick during winter (Manabe and Stouffer, 1980). Thinner ice in winter will facilitate the transfer of large amounts of heat from the ocean into the atmosphere and increase surface air temperatures. If the theory is correct, early signs of the CO_2 impact should appear in the Arctic by accelerated snow dissipation in late spring and increased ice dissipation in summer and also in an increase of cloud cover due to higher evaporation. The arctic melt season is short and any change in its timing and in the extent of the area affected has a large impact on the energy budget of the region (Marshunova and Chernigovskii, 1968).

We present here an arctic-wide analysis of late spring and summer cloudiness using satellite data. Such an effort, if continued for a sufficient time, should enable improved cloud parameterization in climate models used to assess the impact of CO_2 and atmospheric aerosols on high latitude climate. It should also enable future detection of secular changes in high latitude cloudiness which are expected to result from increasing CO_2. Our present results are based on 57 daily cloud cover charts derived from imagery from the Defense Meteorological Satellite Program (DMSP). The data were analysed in 2-7 day intervals for June and July 1977, mid-May to mid-August 1979 and at selected intervals of the spring and summer of 1978 (cf. Figures 1 and 2). Cloud thickness was mapped in three classes in all charts and relative cloud top height at three levels was distinguished in mid-month charts. Data were subsequently compared with surface pressure charts. The results presented are an expansion of a previous Lamont-Doherty Geological Observatory report (Kukla, 1984), which was based on the analysis of 1979 data.

The large-scale melt of pack ice in the central Arctic begins when low-level optically thick stratus moves into the area (Untersteiner, 1961). These clouds are variously interpreted as of autochthonous origin or as allochthonous formations produced by cooling of moist air parcels advected from lower latitudes (Herman and Goody, 1976; Tsay and Jayaweera, 1984). Although the presence of clouds at the start of snow and ice dissipation seems to be critical, details of the role of clouds in the initiation and maintenance of the snow and ice melt are not sufficiently known. Previously available information on the large-scale seasonal distribution and dynamics of arctic clouds is inadequate. This is because the automated identification of clouds from satellite imagery in the presence of snow and ice is currently unsatisfactory and ground station reports come either from a few isolated drifting ice camps or from coastal stations. Reports from ice floe camps only cover a few years at most, during which time a station continuously changes position. Coastal reports are sufficiently long but, because of specific cloud regimes at the land-ocean boundary, can not be considered representative of the Arctic interior (Jayaweera, 1977; Barry, 1983).

Previous studies of arctic cloudiness present conflicting results. The charts of Vowinckel and Orvig (1970) show 90% cloud cover in the basin in July. Huschke (1969) and Marshunova and Chernigovskii (1971) calculate 80-90% cover with little variation from June to August. Out of this total, 70-75% is reported to be low level clouds (Gavrilova, 1963; Huschke, 1969). Other reports do not leave an impression of relatively low month-to-month variability of cloudiness throughout the summer. For instance, in 1950 at 78°N-170°W, Chukanin (1954) reported a monthly cloud cover of 96% with 88% of it of the low variety in June, 78% total with 56% low in July, and 91% total with 79% low in August. Jayaweera (1977), in 1975 at the Big Bear camp in the Beaufort Sea, saw similar large month-to-month variations of stratus ranging from 55% in June to 80% in July. Simultaneous determination of large scale cloud coverage in the Beaufort Sea from NOAA Very High Resolution Radiometer (VHRR) satellite images showed an average of approximately 40% cover in June and 50% in July.

2. DATA SOURCES

Clouds were charted from shortwave (0.4-1.1 μm) and infrared (8.0-13.0 μm) DMSP imagery. The polar-orbiting satellites employed in this study crossed the equator at local noon in all cases, with the exception of July and August 1979, where noon and dawn/dusk equatorial crossing satellite imagery was also used. All satellites were equipped with an Operational Line Scan System Sensor (OLS) with a nadir resolution of 0.6 km. Most imagery used in our analysis was degraded to a resolution of 2.8 km. The OLS provided a near-constant image resolution with optical compensation for motion across the 3000 km scan tract. In the shortwave, bi-directional reflectance of the earth-atmosphere system is recorded and theoretically normalized for solar illumination. Gain changes, however, are not smooth at the low summer solar elevations in the Arctic, which, in addition to difficulties in snow-cloud differentiation, prevents a successful automated shortwave analysis of arctic cloudiness.

Daily DMSP imagery is available in Transverse Mercator projection on ungridded positive-film transparencies scaled at 1:15 x 10^6. The processed film density is linearly proportional to scene reflectivity in the shortwave and grey shades, signifying temperature, in the infrared. Digital data are not archived and are unavailable. Further details on DMSP imagery are found in Appendix 1 and in Fett and Bohan (1977).

Surface pressure data were culled from daily National Meteorological Center (NMC) 00Z Northern Hemisphere charts to maintain a homogeneous record for 1977-1979 (cf. Figure 3). We are aware of the availability of pressure data from the Arctic Ocean Buoy Program in 1979, and they were used in case studies involving the tracking of cyclonic systems within the basin. A comparison of NMC and buoy data showed the NMC fields to be "remarkably good" in the polar region (Thorndike and Colony, 1981).

3. PROCEDURE

a. Charting of cloud thickness:

While the visual identification of clouds from snow and ice fields using shortwave and/or infrared imagery is a time comsuming task, the automated retrieval of clouds, particularly low level clouds, remains unsatisfactory. This is because clouds, snow and ice have similar surface brightnesses in the shortwave and similar temperatures in the infrared. At times the cloud tops may be warmer than the surface due to inversions. We have visually differentiated clouds from snow and ice, primarily by the characteristic large-scale features of the pack ice fields identified in shortwave imagery. These include:

1) elongated leads filled with water or grey ice, contrasting with the brighter snow or older ice fields.

2) snow-covered floes of multi-year ice separated by darker ice or water.

3) patchy fields of grey melting snow and/or meltwater puddles separated by bright snow and ice pressure ridges.

Depending on the cloud optical thickness, these features are either completely or partly obscured.

In addition, certain cloud fields, particularly those located in cyclonic regions, are recognized by their characteristic shapes and patterns, which are often evident in both the shortwave and infrared imagery.

Charts of cloud cover, showing cloud-free skies as well as relative cloud thickness and height, were prepared on a scale of 1:15 x 10^6, matching the DMSP transparencies (cf. Figures 1 and 2). Our visual interpretation was assisted by an interactive analysis using a digital image processor. The processor was used primarily to determine cloud thickness categories (cf. Robinson et al., 1983). Multiple images for a given date were combined to permit coverage of as much of the Arctic Basin as possible. Imagery from several adjacent passes separated by as short a time interval as possible were used to minimize the distortion due to moving clouds. Missing or poor quality imagery resulted in data gaps in some of the charts (cf. Appendix 2).

Four cloud cover classes, including three cloud-thickness classes and a cloud-free class were recognized:

Class 1: cloud-free (surface features seen with high contrast)

Class 2: thin clouds (surface features clearly recognizable but with reduced contrast from cloud-free skies)

Class 3: moderate clouds (surface features marginally recognizable through the cloud)

Class 4: thick clouds (no surface features recognizable)

b. Charting cloud top height:

Interpretation of cloud top height relied primarily on the distinction between grey shades on infrared images and their relationship to cyclonic weather systems. Above any potential inversion layer, the higher clouds are colder. They appear brighter than the lower clouds and the cloud-free pack ice in infrared imagery. Only the Greenland ice sheet may appear similarly bright. The height analysis was supplemented by shortwave images, where estimates of cloud top height were made from the length of shadows cast on the ice surface, knowing the solar zenith angle.

The primary limitation to the height analysis is where high clouds are thin yet may be estimated as having middle or low tops using the infrared analysis technique. This is because the temperature of an area with high thin clouds is a function of these clouds as well as warmer clouds, land and/or ocean surfaces lying under them. The lack of recognizable shadows cast by these clouds prohibits estimates to be made using shortwave imagery. It is uncertain how large an impact this limitation has on our results. However, we believe it to be minimal, as analyses of cloud bands which were identified as having high tops over areas where they were underlain by thick clouds continued to be recognized as high when over regions with no clouds below them. This persisted until they reached dimensions considerably smaller than the grid cells used to digitize the data (cf. section 3-d).

Three cloud height classes were recognized:

Class 1: high level (brightest, cold; usually associated with well defined cyclonic weather systems of several hundred kilometers or greater extent)

Class 2: middle level (intermediate grey values, cool; generally sharply defined from areas with high level cloud, low clouds and the surface. Usually associated with well defined cyclonic systems)

Class 3: low level (darkest in the infrared, relatively warm, sometimes warmer than the surface, not previously defined as cloud-free sky. Usually not associated with well defined cyclonic systems)

Detailed descriptions of the procedures used for charting cloud thickness and height are found in Appendix 1.

c. Digitization of data:

Cloud and pressure charts were digitized using the National Meteorological Center's standard Primitive Equation data grid (Figure 4), used previously in a satellite-based earth radiation budget atlas (Winston et al., 1979) and an atlas of satellite-derived snow cover data (Dewey and Heim, 1981). For cloud charts, a grid cell was categorized according to the predominant cloud thickness or height class within it. Only those cells where more than 50% of the area had data were counted. Surface pressure charts were digitized by choosing the largest area between isobars within a cell and assigning the cell the average value of the two isobars.

d. Regions charted:

While clouds were charted over a broader area (cf. Appendix 2), five regions of the Arctic Basin were selected for analysis, each containing from 35 to 146 NMC grid cells (Table 1, Figure 5). Regions were defined as follows:

R1: Inner Arctic Ocean: A 35 cell block centered on the North Pole with no cell containing any land.

R2: Outer Arctic Ocean: Cells situated north of 70° in the Greenland and Barents Seas where seasonal and multiyear ice accumulates and all cells in the Arctic Ocean not lying in regions R1 and R3.

R3: Arctic Coastal Water: Cells bordering the northern coasts of Asia east of 45°E and North America west of 125°W and lying north of the Bering Strait which contain some, but less than 50%, land. In addition, those cells lying next to these which contain no continental land are included in this region.

R4: Canadian Archipelago: Cells containing the islands and waters of the archipelago north of the Arctic Circle.

R5: Arctic Coastal Land: Cells bordering the arctic coast west of 125°W and east of 40°E lying north of 65° which contain some, but less than 50%, water.

Data coverage was best in the Inner Arctic (cf. Appendix 3), approaching 100% of the grid cells on all charts in all years. This high percentage was found for regions R2-R4 in most 1978 and 1979 charts. Region R5 in 1978 and 1979 and regions R2-R4 in 1977, on the average, had between 60 and 80% cell coverage. Only region R5 in 1977 averaged less than a 50% coverage.

e. Confidence limits:

As charts were primarily constructed through a visual interpretation of satellite imagery and subjectively counted, tests were conducted to assess the agreement between different analyst's interpretations of identical imagery. Six mid-month cloud-cover charts for June and July 1977 and May-August 1979 were independently constructed by two interpreters. Reasonable agreement was found for all charts. The average coverage of classes 1 and 2 combined for the 6 charts differed by 8%. Individually, class 1 (cloud-free) showed the best agreement, differing by only 2%. The largest differences were in the delimiting of moderate against thick clouds. This was expected, as it is the most difficult distinction to make. These two will therefore be frequently combined in the following analysis.

f. Representativeness of study results:

Limitations of our study are as follows:

1. Individual charts are multi-temporal mosaics. They do not represent any single instant of time over the entire Arctic Basin. Individual sections of a chart are several hours apart and each particular area was charted only once in a given day. Due to the general sluggish movement of weather systems (and clouds) within the basin, these limitations are not likely to introduce a serious bias into the analysis. Figure 6 shows the slow movement of a June 1979 low pressure system, which took two weeks to progress across the basin. The diurnal cycle of cloud cover common in lower latitudes is likely to be suppressed or nonexistant at this time of the year when the sun is continually above the horizon.

2. Charts are separated by intervals of 2 to 7 days. This sampling frequency is insufficient to give accurate monthly means. Therefore, our results should be considered as only estimates of monthly and seasonal means for 1977 and 1979. These should be reasonable estimates, given the sluggish movement of summer weather systems and the probable suppressed

diurnal cycle of cloud cover.

3. Because data from only 3 years were analysed, the results should not be taken as a late spring and summer cloud climatology of the Arctic. It is unknown to what degree the cloud conditions in 1977-1979 are representative of typical arctic summers. Reports from earlier years (eg. Huschke, 1969; Vowinkel and Orvig, 1962; Beryland et al., 1980), drawn primarily from ground station data, show cloudier summer conditions than we have observed (cf. section 4-a+b). The question of whether cloud conditions have either changed since the time of ground data collection (prior to 1970), or reflect differences in ground and satellite products (due to a ground observation bias leading to an overestimation of cloud cover (cf. Appleman, 1962)) is unlikely to ever be answered adequately. Continued monitoring is needed to identify any future trends in arctic cloudiness, if they exist.

4. RESULTS

a. Time related change of cloud cover extent:

Figure 7 gives an example of a digitized cloud cover chart produced from the original shown in Figure 1. All daily cloud cover charts for 1977 and 1979 are shown in digital form in Appendix 2 and for 1978 in Appendix 6. All digitized cloud thickness and height data and pressure data are available on magnetic tape from the Department of Energy's Technical Information Center in Oak Ridge, Tennessee or from the authors. Cloud amounts are summarized by region and cloud class and shown for 1977 and 1979 in Appendix 4. Figures 8-13 are plots for region R2 (Outer Arctic Ocean) in 1977 and Figures 14-19 are for region R2 in 1979.

Cloud cover was variable across the Arctic Basin in space and time in 1977, 1978 and 1979. Fluctuations in the percent of cloud cover by class from one chart to the next were generally within 10% in each region, but occassionally ranged up to 50%, particularly in the Canadian Archipelago (R4) and Coastal Land (R5) sectors. The Inner Arctic (R1) had the most extensive and thickest cloud cover, followed in order by the Outer Arctic (R2), Arctic Coastal Water (R3), R5 and R4. In 1977, the beginning of June and the end of July were cloudiest, separated by a period of reduced cloud cover in late June and early July. In 1979, the second half of May and the first half of June had the most cloud cover, particularly of classes 3 and 4.

In region R2, the combined percentage of cloud-free skies and thin clouds (classes 1 and 2) in 1977 was approximately 20% until the June 19 chart (Figure 12), while in the June 25 and 28 and July 1 charts the proportion was close to 60%. Subsequent charts for late July show increasing cloud cover, similar to early June values. In 1979, the relatively cloud-free summer interval apparently did not occur (Figure 18). However, after a cloudy period in late May and early June (the first 10 charts), when thick and moderate clouds (classes 3+4) covered over 60% of the region (Figure 19), half of the 22 remaining charts had less than a 60% coverage of these classes.

Comparisons of the 1977 and 1979 cover of cloud classes 3 and 4 over the Inner (R1) and Outer (R2) Arctic Ocean, the two cloudiest regions, and over the Canadian Archipelago (R4), the least cloudy region, are plotted in Figures 20 and 21, respectively. The ocean regions showed less year to year variability than the archipelago, where the frequently large differences between 1977 and 1979 also exemplify the large chart-to-chart fluctuations of cloudiness in the region.

In 1978, the mid-month charts showed the Inner Arctic (R1) to have fewer clouds in May than in the following three months. The archipelago (R4) and Coastal Land (R5) had more clouds in

May than in the middles of June, July and August. Mid-June was cloudier than mid-July in all regions except the archipelago and mid-August was cloudiest over regions R1, R2 and R4.

b. Extent of cloud cover - estimates of monthly means:

Data for the nineteen 1977 and thirty-two 1979 charts were averaged for each year into monthly mean estimates for all regions and cloud cover classes (Table 2, Figures 22-27). May and August 1979 results apply only to the last and first half of these months, respectively. Charts showing the frequency of classes within the basin are found in Appendix 5, with Figures 28-31 examples of a monthly set of these charts for July 1979.

Moderately thick clouds (class 3) were most abundant in all regions and in all months charted, with the exception of regions R4 and R5 in July 1979, R4 in August 1979 and R3 and R4 in July 1977 when cloud-free skies (class 1) dominated. Another exception was region R1 in July 1977 and August 1979 when thick clouds (class 4) prevailed. Thin clouds (class 2) never dominated a regional monthly mean. Classes 3 and 4 combined covered more than 50% of each region in all monthly means, with the exception of region R4 in July 1977 and July and August 1979 and R5 in July 1979. However, only in R1 in July 1977, June 1979 and August 1979 was a region covered with greater than 75% thick and moderate clouds.

The estimated mean monthly cloud cover within each region varied little in June and July of 1977 and 1979. While interesting, this may not be representative of every year in the Arctic. Figure 32 shows a graph of class data for region R2 in the four 1977 and 1979 months combined which may be considered representative of the other regional results. Class 3 was the most abundant, classes 1 and 4 had similar coverage and class 2 was the least abundant. In these four months, cloud-free skies and thin clouds combined covered an average of 23% of the sky in region R1, 37% in R2, 42% in R3, 51% in R4 and 47% in R5.

c. Cloud top height:

Twelve mid-month charts of cloud top height were constructed for the 15th of May through the 15th of August from 1977 to 1979. The height of the cloud top was differentiated into three classes and compared with cloud thickness. Examples of both of these charts are shown in digital form in Figures 33 and 34 for July 15, 1977, with all charts found in Appendix 6. No monthly or interannual differences were observed between charts. Therefore, all twelve were combined and analysed by region, with regions 1 and 2 combined (Figures 35-38).

The vast majority of clouds throughout the Arctic Basin had cloud tops at the low or middle level. As plotted in

Figures 35-38, thicker clouds tended to have the higher tops. Over ocean areas (regions R1-R3) 70% of the moderately thick clouds were low. Over coastal land (R5) this percentage was 60% and it was only 45% over the archipelago (R4). Over ocean areas there were approximately equal amounts of thick clouds with middle and low tops. Middle-level thick clouds dominated the regions containing some land (R4 and R5) and high thick clouds were noted just as frequently as low thick clouds over the coastal land (R5).

d. Pressure/cloud relationships:

Moderately thick and thick cloud cover combined (classes 3+4) and cloud top height were compared to coincident surface pressure for the 57 charts in 1977-1979. Digitized daily and mean monthly pressure fields, estimated from chart date data only are shown in Appendix 7. Examples of monthly pressure charts and charts showing the frequency of cloud classes 3 and 4 are shown in Figures 39-42 for June and July 1979. Daily cloud cover (classes 3+4) and pressure data are plotted in Figures 43 and 44 for region R2 in 1977 and 1979, respectively. All regions are shown in Appendix 8.

Figures 39-44 illustrate the close relationship between moderate and thick cloud cover and pressure observed throughout the Arctic in the late springs and summers of 1977 and 1979 and also recognized in the mid-month charts in 1978. For instance:

1. In July 1979 (Figures 41 and 42), moderate and thick cloud cover was least extensive over regions of high pressure and most extensive where pressure was low. This situation was quite common throughout the basin, particularly in region R2 from mid-June onwards, where 26 of the 32 chart dates had an inverse relationship between above and below average pressure and cloud coverage (Figures 43 and 44). Average for each region is defined as the mean of all 1977 and 1979 charts covering the region.

2. Prior to June 15, both pressure and the coverage of moderate and thick clouds tended to be above average. After the middle of June, below average cloud cover was associated with below average pressure in 75% of the cases where an inverse relationship did not exist.

3. The 1977-1979 charts also show abundant moderate and thick cloud cover in areas of southerly (offshore) flow. Figures 39 and 40 illustrate such a case, with heavy cloud cover along the 90°E meridian from the coast to the pole. A tendency towards onshore (northerly) winds or winds paralleling the coast to be associated with less cloud cover over coastal waters was seen in July 1979 (Figures 41 and 42) along the Alaskan coast into the archipelago.

Pressure data over the Arctic Ocean (regions R1-R3) were compared to cloud top height in mid-month charts from May-August 1977-1979 on a grid cell level (Figure 45). Out of a possible 738 cells compared in a given month, a cloud thickness/height relationship (ie. thick clouds with high tops) was plotted in the figure only if it was found in more than 15 cells. Most of the categories plotted in the figure were found in over 50 cells, with several approaching 200. Results show that cloud-free areas averaged close to the highest pressure of all categories in all months except June; whereas areas with thick high clouds averaged the lowest or close to the lowest pressure in all categories each month. The mid-June pressure was lowest in all categories, except where clouds were thick with high tops. May pressure was highest in all categories plotted.

5. DISCUSSION

a. Absolute optical thickness and cloud top height estimates:

Up to this point, no estimates of absolute cloud optical thickness or cloud top height have been made for each visually derived class. We do so now only as a rough guide and to serve as encouragement for conducting future coordinated multi-platform experiments to add information to that already gained in earlier aircraft studies.

Optical thickness estimates are partly based on a comparison of flight data gathered in the summer of 1980 (Tsay and Jayaweera, 1984; Herman and Curry, 1984), with coincident satellite derived cloud charts constructed in the same manner as the previously discussed DMSP set. NOAA Advanced VHRR imagery in the visible channel was used in the analysis, but, for our purposes, the results will be assumed to directly relate to the broader band DMSP imagery. According to this analysis (Table 3), multi-layer relatively thick cloud with a high liquid water content and with a grey optical thickness of about 25 corresponded to cloud cover class 4. Cloud charted as class 3 had a moderate liquid water content and an optical thickness of around 8-10. Clouds in class 2 could not be directly correlated with the flight data but should have a low to very low liquid water content and an optical thickness of between 2 and 5. More information on the comparison is in an earlier report (Kukla, 1984).

Optical thickness was estimated in a different manner by employing image processor measurements of the contrast in DMSP satellite observed brightness between snow and open water surfaces for clear and cloudy conditions in a detailed radiative transfer model (Robinson et al., 1983). Tentative estimates of optical thickness drawn from this approach suggest class 2 clouds may have optical thicknesses as low as 2 and class 4 clouds thicknesses as high as 40.

We roughly estimate that the tops of the clouds classified as low level are below 1000m, middle level clouds between 1000 and 4000m and high level clouds over 4000m. These estimates are based on in situ measurements (Herman, 1977; Tsay and Jayaweera, 1983 and 1984; Herman and Curry, 1984) and other published sources (Reed and Kunkel, 1960: Cogley and Henderson-Sellers, 1984).

b. Role of advection:

Others have discussed the positive relationship between warm advection and increased cloudiness in the basin (eg. Reed and Kunkel, 1960; Jayaweera, 1982). Examples of this in the present study were noted in daily charts. For instance, in

1979, an increase of thick cloudiness in the basin was associated with the arrival of a low pressure system (cf. Figure 6 and Appendix 2). This system, which crossed the North Pole on June 13 and dissipated over Baffin Island a week later, apparently brought relatively humid air into the Arctic Basin from the Asian continent. The Arctic Ocean was still almost entirely ice covered, so it could not have served as the primary source of the moisture. A low pressure system which developed in the Beaufort Sea in early June 1979 and pulled in continental air from Alaska and Canada was also associated with the occurrence of thick clouds. Monthly charts showed increased cloud cover in areas of advection and diminished cloud cover in areas where the flow was out of the basin (cf. section 4d and Figures 39-42).

The coastal and archipelago regions (R3-R5) were seen to have greater day-to-day variability in cloud cover than ocean regions (R1 and R2) (cf. Figures 20 and 21; Appendix 4). The former are in areas where frequent fluctuations in atmospheric temperature and moisture occur, which are associated with changes in wind direction.

6. CONCLUSIONS

Our results show that the extent and thickness of clouds and the height of cloud tops in the Arctic Basin were heterogeneous in space and time in the late springs and summers of 1977-1979. While clouds often covered greater than 50% of the basin, relatively cloud-free episodes, which were found in all areas of the basin, persisted long enough (days to weeks) to significantly affect the surface radiation budget and therefore the dissipation of snow and ice cover.

As the majority of clouds over the basin were partly transparent, they should have allowed a high amount of incoming solar radiation to penetrate to the surface. If this is a common feature in most years, it may have important implications in terms of the earth/atmosphere energy budget and the role of summer arctic cloudiness in any future climatic change.

Should the the increased atmospheric moisture associated with a CO_2 warming or increased turbidity of the air advected to the Arctic increase cloud opacity and reduce the amount of shortwave radiation reaching the surface, the timing of important regional processes such as surface melt and the resultant decrease in surface albedo may be altered.

Further monitoring of arctic cloudiness should serve as a means for recognizing and assessing the impact of any climatic change. Climate models used to assess the impact of CO_2 and other trace gases on the earth's climate should adequately parameterize cloud cover to reasonably model the radiation budget of the basin.

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Table 1. Regions studied in the Arctic Basin (cf. Figure 5). The number of grid cells (cf. Figure 4) in each region is also listed.

Region	Grid cells
R1. Inner Arctic Ocean	35
R2. Outer Arctic Ocean	146
R3. Arctic Coastal Water	65
R4. Canadian Archipelago	55
R5. Arctic Coastal Land	41

Table 2. Mean monthly estimates of percent cloud cover by region. Cloud classes include: cloud-free (1), thin clouds (2), moderately thick clouds (3) and thick clouds (4). Regions are listed in Table 1 and shown in Figure 5. Mean values were derived by averaging charts separated by intervals of 2-7 days during a given month. May and August 1979 means are for the last and first half of the month, respectively. Means are listed only if data were available from 50% or more of the total potential grid cells in a given month and region.

Date	Region	Cloud class			
		1	2	3	4
June 1977	R1	20	03	43	34
	R2	20	11	49	20
	R3	31	06	49	14
	R4	40	06	49	05
	R5	34	02	48	16
July 1977	R1	21	06	28	45
	R2	27	13	37	23
	R3	38	06	36	20
	R4	48	08	35	09
May 1979	R1	17	08	54	21
	R2	10	17	48	25
	R3	09	22	41	28
	R4	25	24	26	25
	R5	19	21	30	30
June 1979	R1	08	09	42	41
	R2	21	18	33	28
	R3	22	20	36	22
	R4	28	18	40	13
	R5	31	14	31	24
July 1979	R1	11	16	38	35
	R2	24	16	32	28
	R3	26	22	26	26
	R4	34	21	33	12
	R5	32	24	20	24
August 1979	R1	15	05	25	55
	R2	12	28	38	22
	R3	16	24	38	22
	R4	33	31	29	07
	R5	26	18	31	25

Table 3. Lamont cloud cover classes compared with the physical properties recorded in the 1980 Arctic Stratus Experiment (from Tsay and Jayaweera, 1983 and 1984; Herman and Curry, 1984) (after Kukla, 1984).

		LAMONT ANALYSIS		NOAA ELECTRA OBSERVATIONS			
Date	Location	NOAA satellite orbit	Lamont cloud type	Optical depth	Maximum liquid water content (g/m^3)	Height (m)	Cloud type
6/13/80	73.9 N 143.6 W	5007	3	5.6	0.287	851	fragmented
6/20/80	73.8 N 159.3 W	5106	3	7.9 9.9	0.393	233	plane parallel single layer
6/28/80	77.1 N 154.3 W	5220	4	24.3 25.5	0.627	1187	multilayered plane parallel

Figure captions

Figure 1. Cloud cover field for July 15, 1979. Classes include:

1) cloud-free (open), 2) thin clouds (light stippling), 3) moderately thick clouds (moderate stippling) and 4) thick clouds (dense stippling). Hatched where data were unavailable. The North Pole is marked on this and subsequent charts with a dark cross.

Figure 2. Cloud top height field for July 15, 1979. Classes include: 1) cloud-free (open), 2) high top (light squares), 3) middle (moderate squares) and 4) low (dense squares). Hatched where data were unavailable.

Figure 3. The arctic portion of the National Meteorological Center's (NMC) Northern Hemisphere 00Z surface pressure chart for July 15, 1979. Add 1000 to all millibar values.

Figure 4. NMC grid used in digitizing cloud and surface pressure charts. Numbers at the corners define the row (sides) and column (top and bottom) designations for the corner grid cells.

Figure 5. Regions in the Arctic Basin used in this study (cf. Table 1 for the region names). Region R1 (squares); R2 (hatching); R3 (light stippling); R4 (moderate stippling); R5 (dense stippling).

Figure 6. Progression of a surface low pressure system across the Arctic Basin from June 4th to June 20, 1979, as taken from NMC 00Z Northern Hemisphere Weather Charts (June 4-6; 17-20) and 1200Z buoy and station data (June 7-16) from Thorndike and Colony (1980). Pressure in millibars (add 900 mb to values >50 and add 1000 mb to values <50). Month and day given in the denominator (from Kukla, 1984).

Figure 7. Cloud cover field for July 15, 1979 in digital form. Numbers on the chart refer to the 4 cloud classes (1:cloud-free, 2:thin clouds, 3:moderately thick clouds, 4:thick clouds). Missing data: 0. Highest and lowest grid row numbers are on the left and highest and lowest columns on the bottom (cf. Figure 4).

Figures 8-13. Daily cloud amounts by cloud class(es) for region R2 in June and July 1977 derived from charts running from June 1 (Julian Day 152 (horizontal scale)) to July 29 (JD 210).

Figures 14-19. Same as Figures 8-13 only for 1979. Charts run from May 15 (Julian Day 135) to August 15 (JD 227).

Figure 20. Comparison of the total amount of moderate and thick cloud cover (classes 3+4) in regions R1 and R2 combined on identical dates in 1977 and 1979. Bars show the difference in the 1977 cloud cover from 1979. The horizontal scale is in Julian Days from June 1 (JD 152) to July 29 (JD 210).

Figure 21. Same as Figure 20 except for region R4.

Figures 22-27. Monthly mean estimates of percent cover for the 3 cloud classes and the cloud-free class in the 5 study regions. For June (Figure 22) and July (Fig. 23) 1977 and May (Fig 24) to August (Fig. 27) 1979. Cloud class symbols same as in Figure 1. May and August 1979 results only for last and first half of months, respectively.

Figures 28-31. Percent frequency of cloud classes 1 (Fig. 28) to 4 (Fig. 31) in the ten July 1979 charts. For a given grid cell a dot indicates that a particular class is plotted in 0-25% of the charts; a * 26-50%, @ 51-75% and # 76-100%. Only those grid cells where at least 7 of the 10 charts had reported data are plotted. Cells with insufficient data are marked with a zero.

Figure 32. Mean cloud cover in region R2 by individual classes averaged from June and July 1977 and 1979 data (thick bar). Stippling denotes the range between the lowest and highest monthly values of the 4 months.

Figure 33. Cloud cover field for July 15, 1977. Classes as in Figure 7. Missing data: 0. Highest and lowest grid row numbers on the left and highest and lowest column numbers on the bottom.

Figure 34. Cloud top height field for July 15, 1977. Classes are 1: cloud-free; 5: low clouds; 6: middle clouds and 7: high clouds. Missing data: 0. Grid cell numbers as in Figure 33.

Figures 35-38. Percentage of total clouds with low (squares), middle (hatching) and high (open) tops within each thickness class. For regions R1 + R2 (Fig. 35); R3 (Fig. 36); R4 (Fig. 37) and R5 (Fig. 38) from an average of mid-month charts in May-August 1977-1979. Percent totals at the bottom of each figure show the percentage of the cloud covered portion of the region having clouds of a given thickness class.

Figure 39. Estimated mean monthly surface pressure field for

June 1979. Derived from NMC charts on cloud chart dates only. Add 1000 to all millibar values.

Figure 40. Percent frequency of moderate and thick cloud cover (classes 3+4) for June 1979. For a given grid cell a dot indicates that classes 3 or 4 are plotted in 0-25% of the charts; a * 26-50%, @ 51-75% and # 76-100%. Only those grid cells where at least 7 of the 10 charts had reported data are plotted. Cells with insufficient data are marked with a zero.

Figure 41. Same as Figure 39, except for July 1979.

Figure 42. Same as Figure 40, except for July 1979.

Figure 43. Percent cover of moderate and thick clouds (classes 3+4) (solid line) and mean 00Z surface pressure (dashed line) on chart dates from June 1 (Julian Day 152) to July 29 (JD 210), 1977 in region R2.

Figure 44. Same as Figure 44 except for May 15 (JD 135) to August 15 (JD 227), 1979.

Figure 45. Mean surface pressure on the 15th of May (M), June (J), July (Y) and August (A) for grid cells over the

Arctic Ocean (regions R1-R3) with particular combinations of cloud cover and height classes. Data are from charts in 1977-1979. Only those combinations of cloud thickness and cloud top height (low:L, middle:M, high:H) which were found in more than 15 grid cells (out of a potential total of 738 cells) were plotted.

FIGURE 1

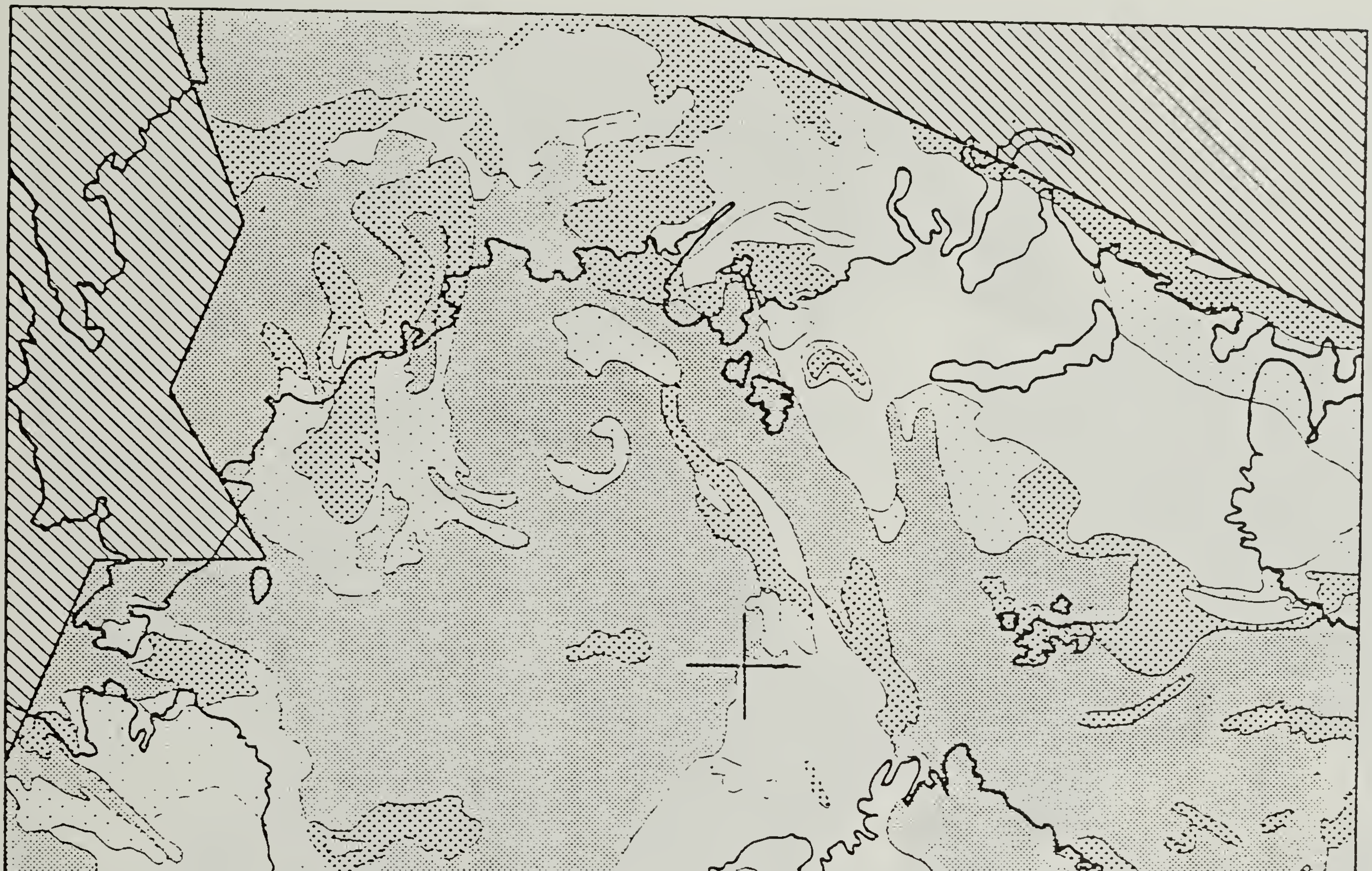

FIGURE 2

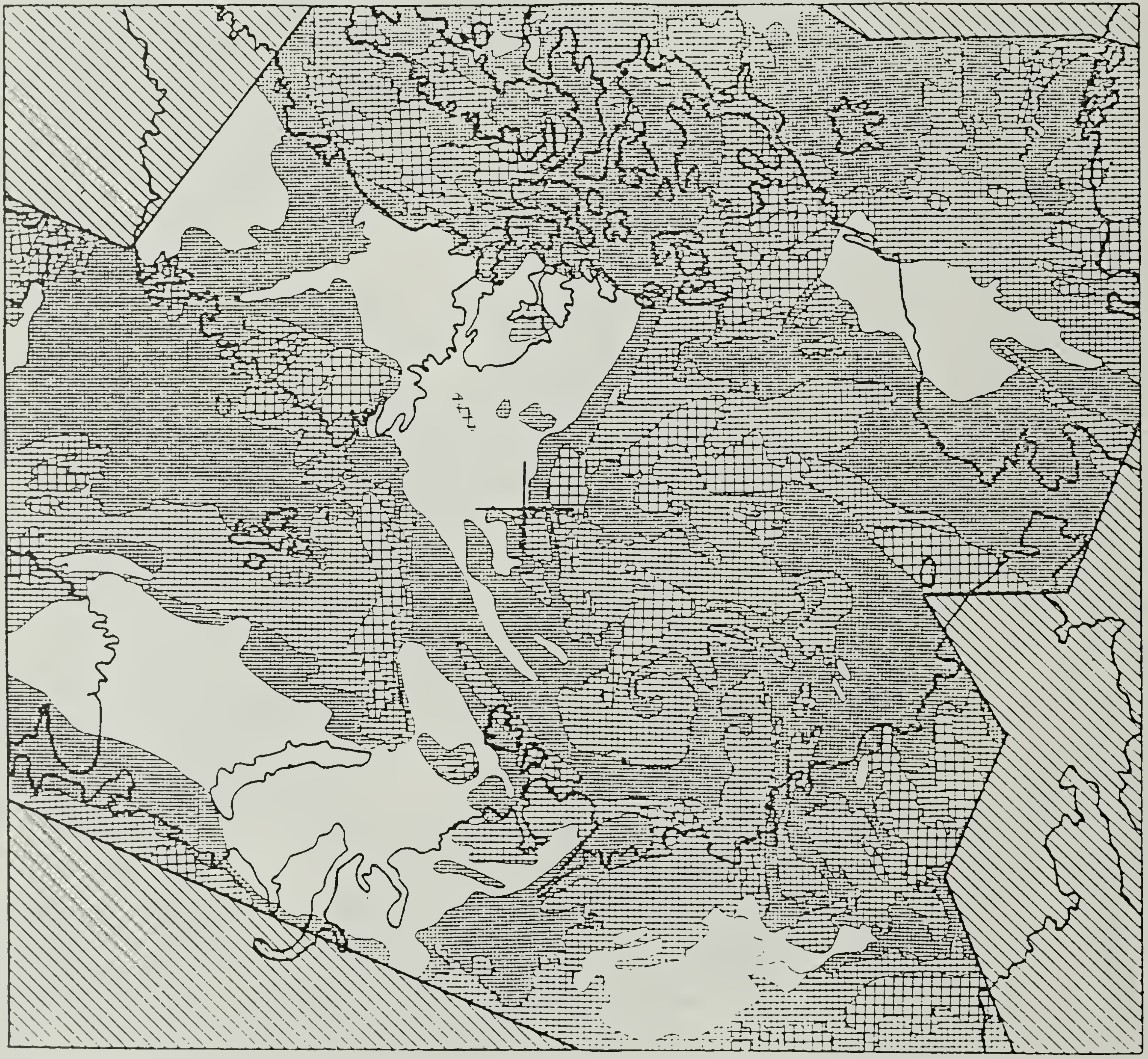

FIGURE 3

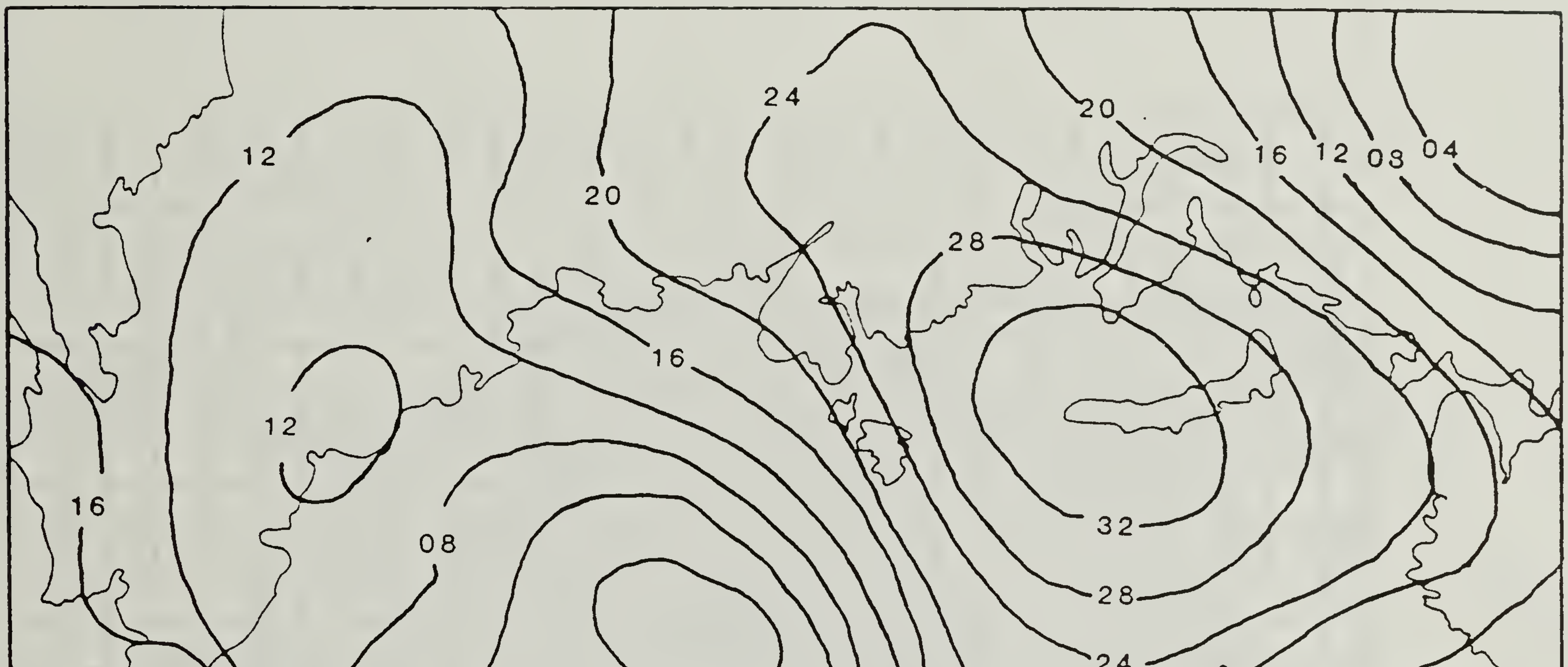
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FIGURE 4

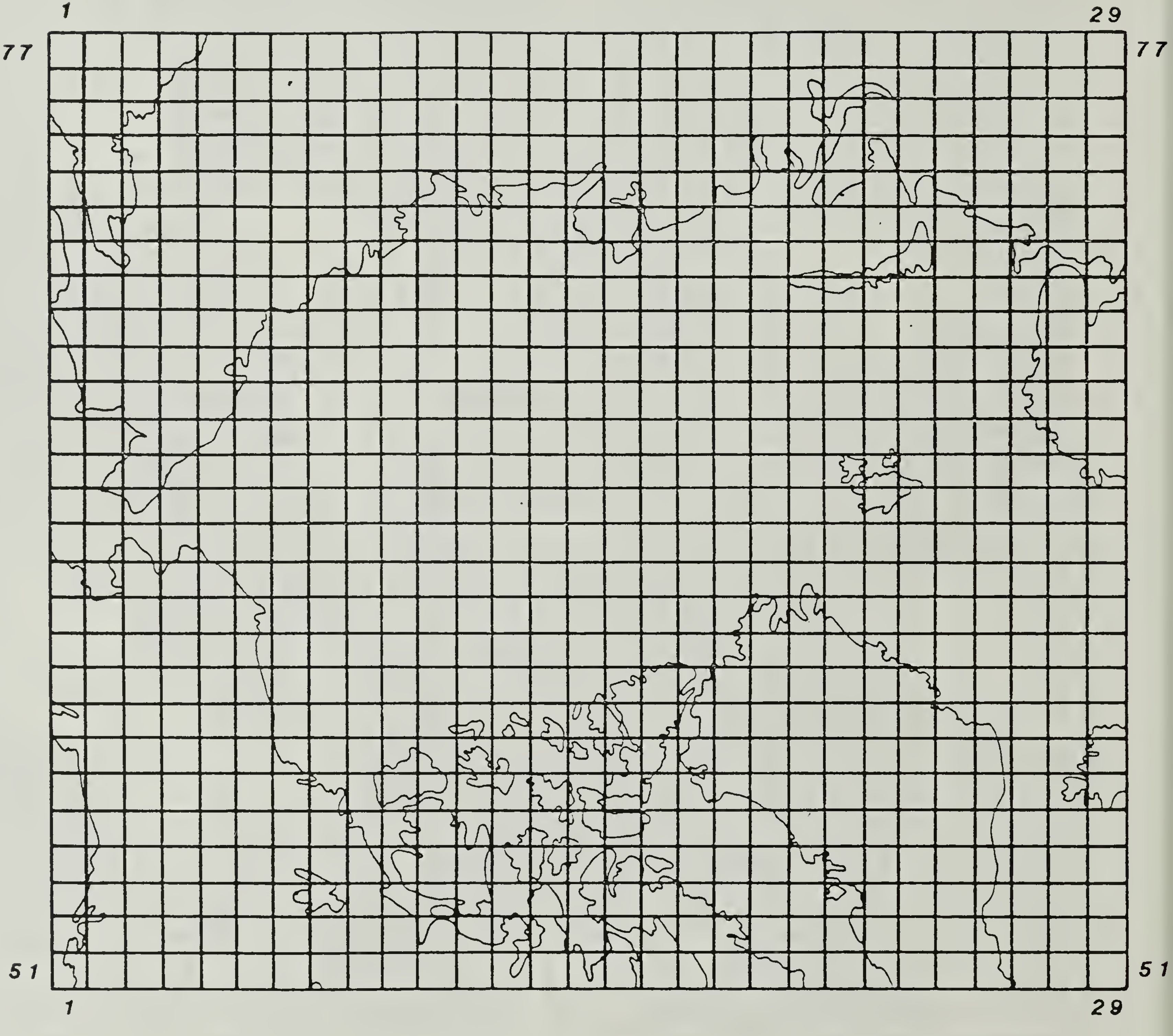
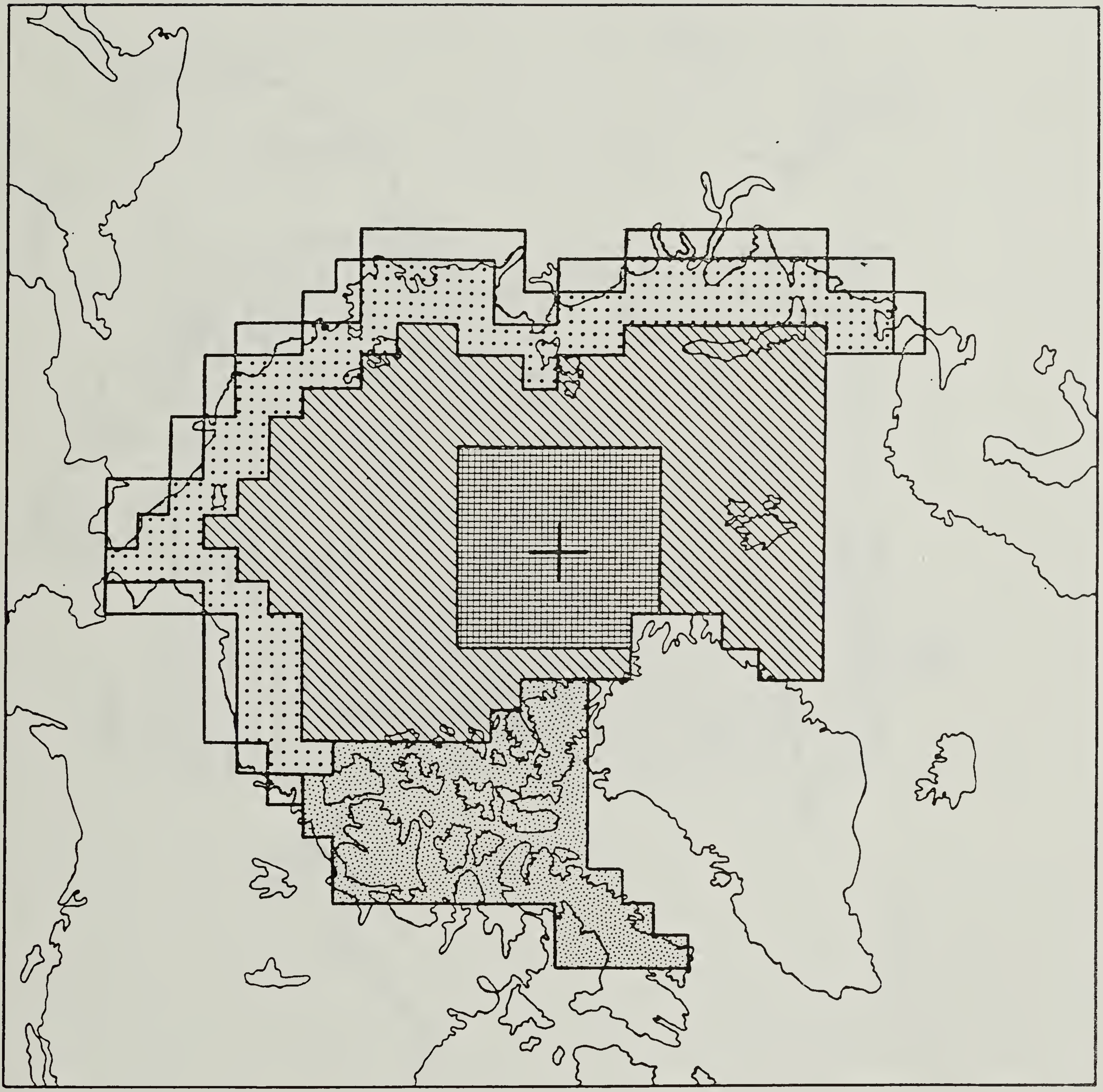


FIGURE 5



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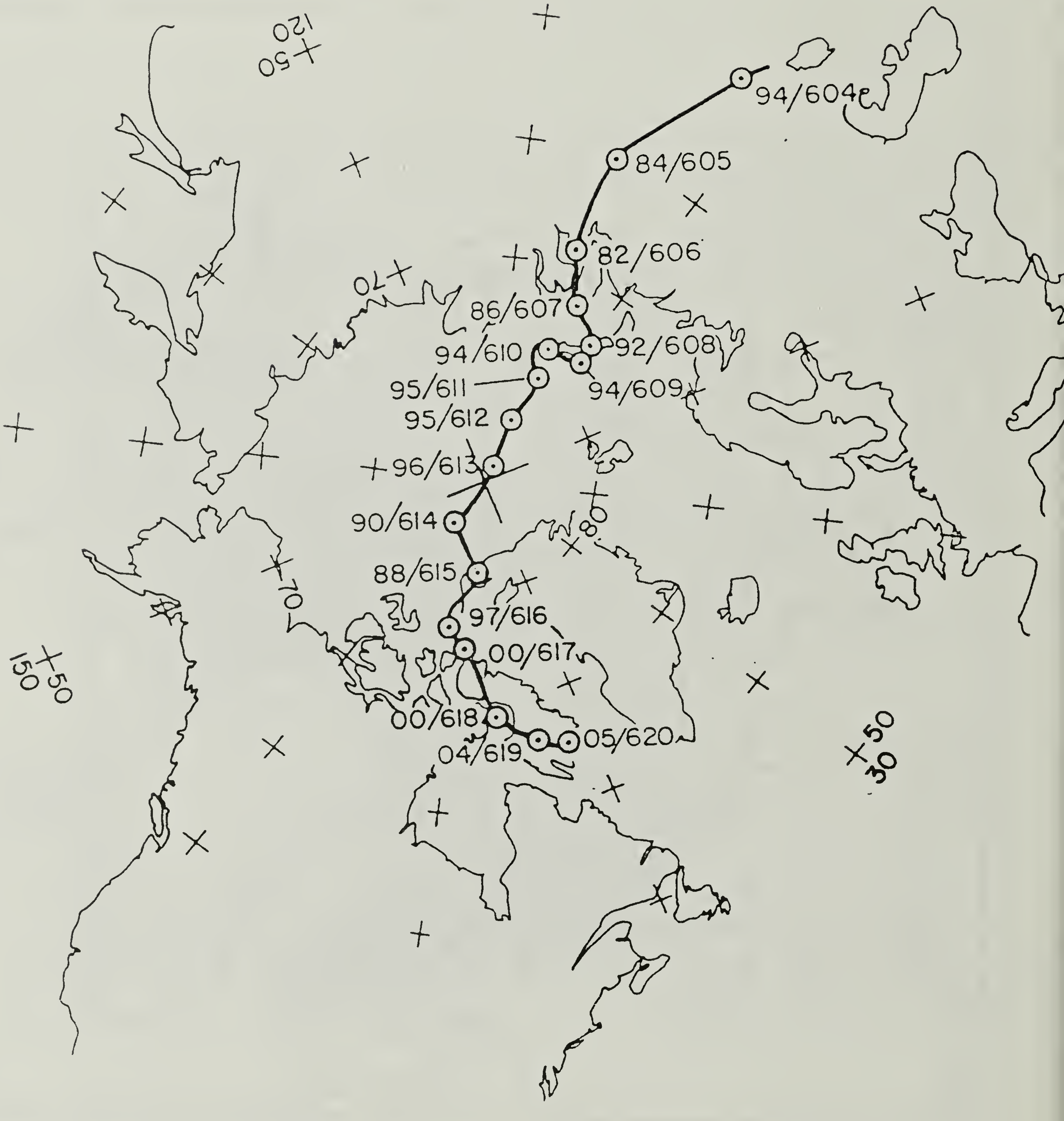
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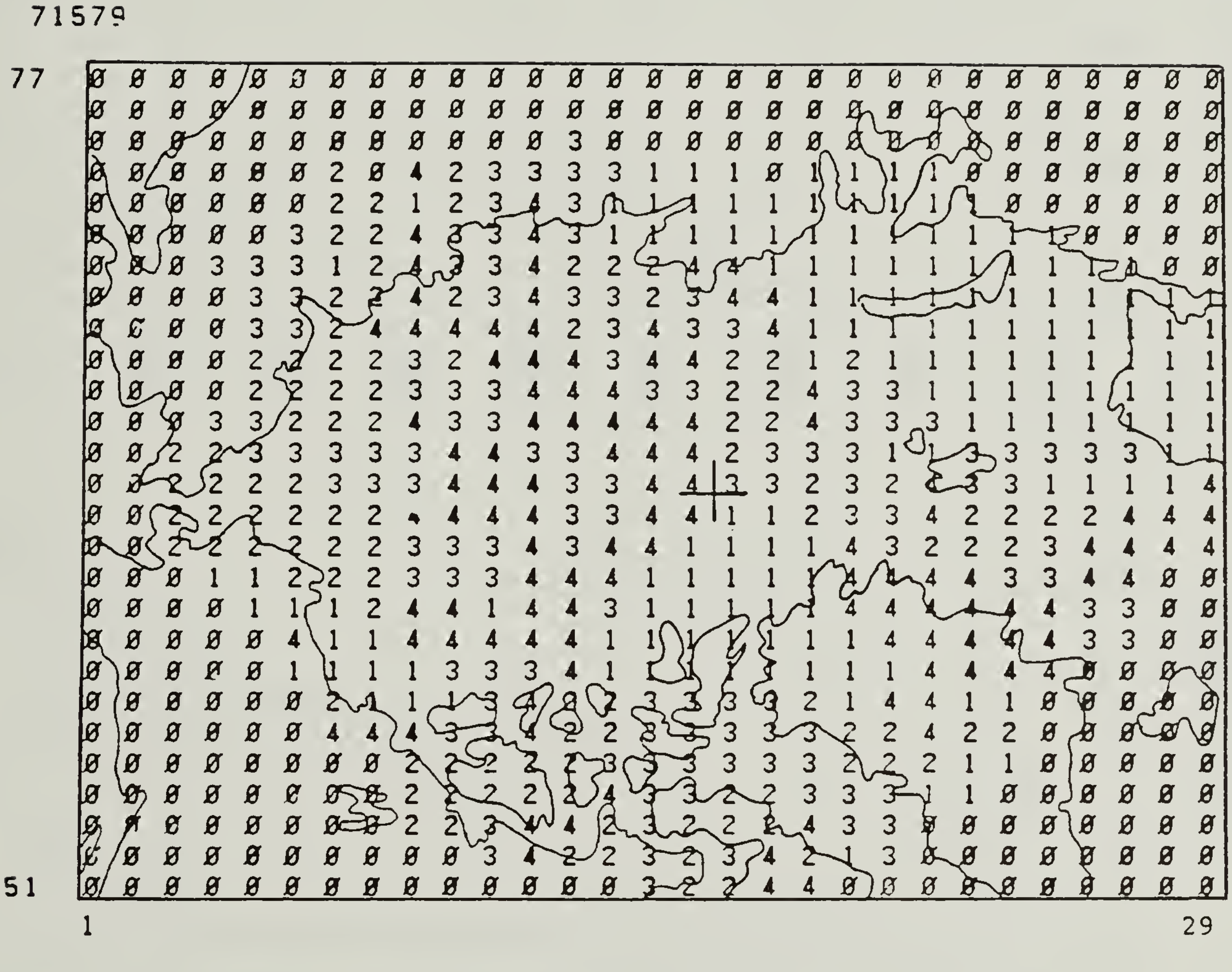
FIGURE 7



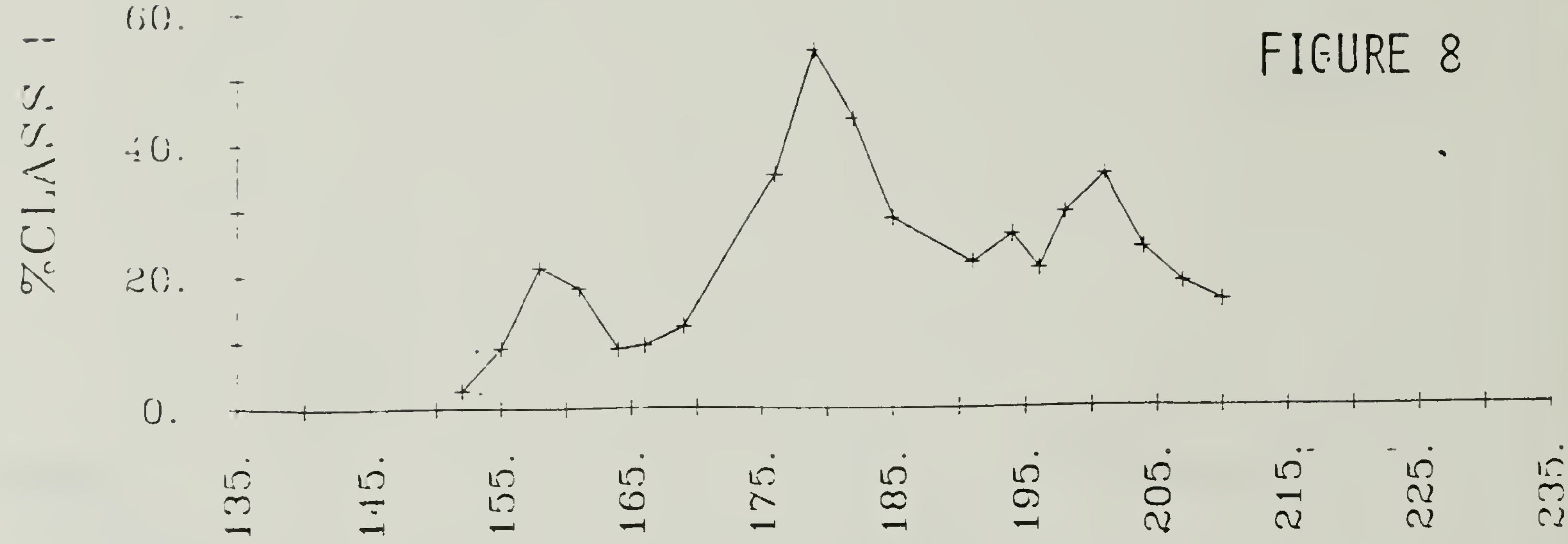
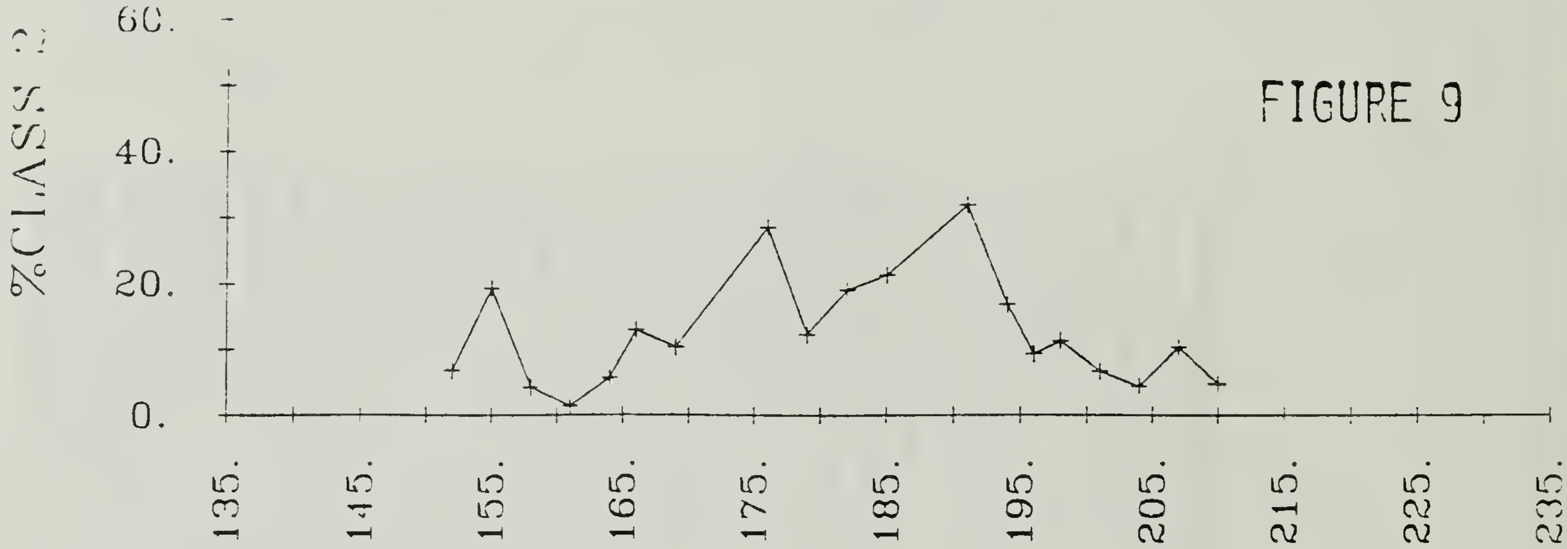


FIGURE 8



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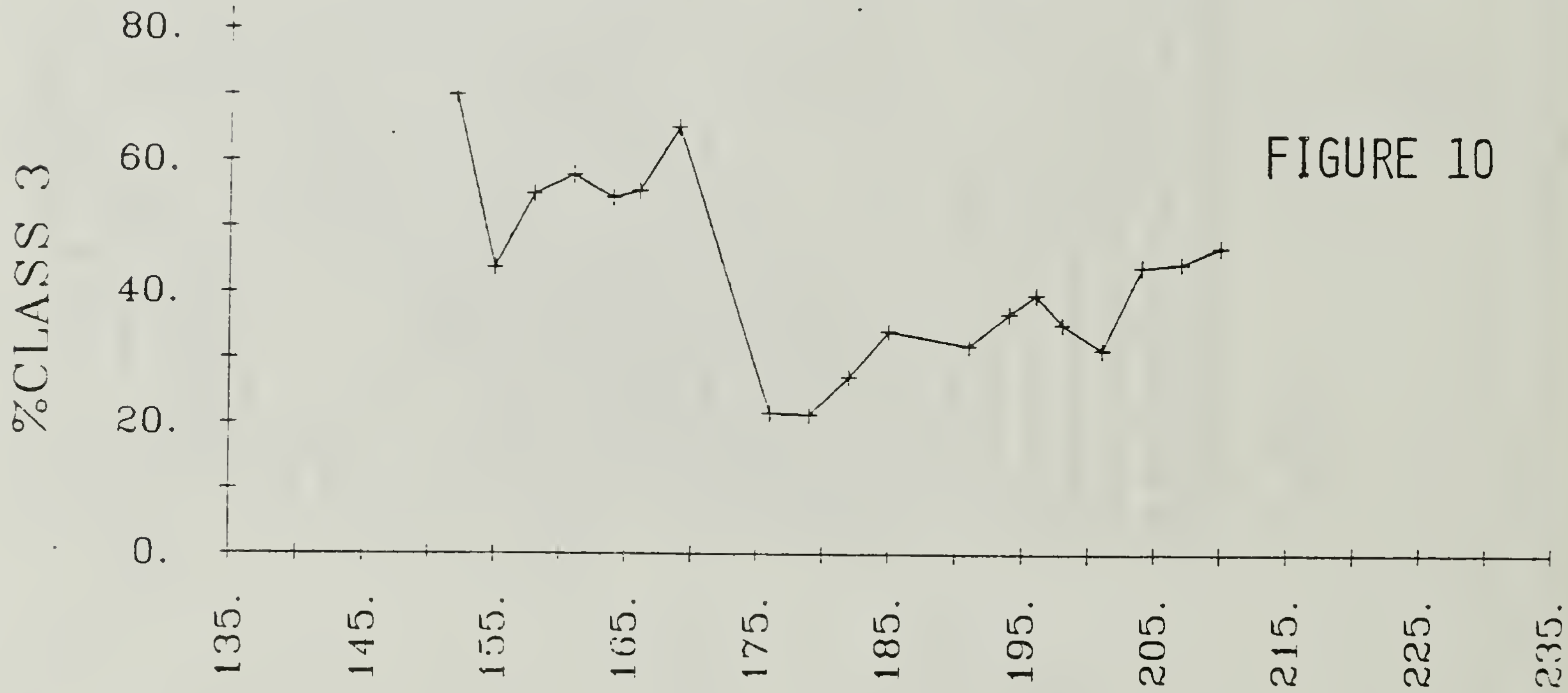


FIGURE 10

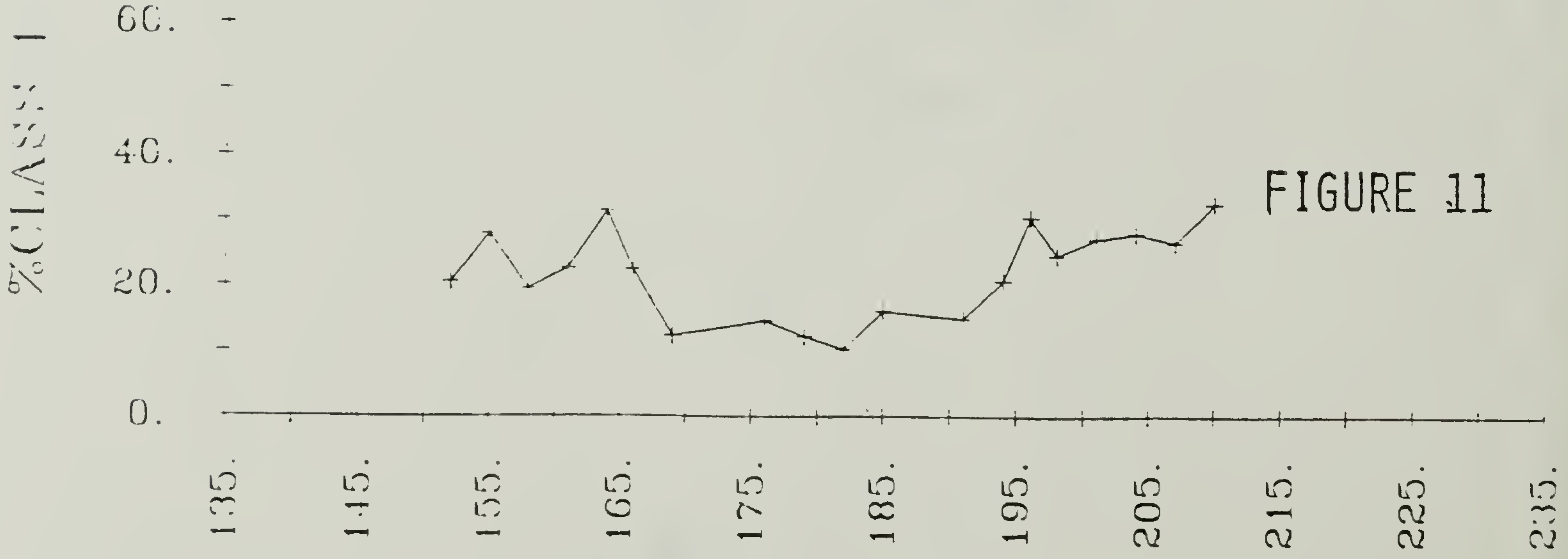


FIGURE 11

FIGURE 12

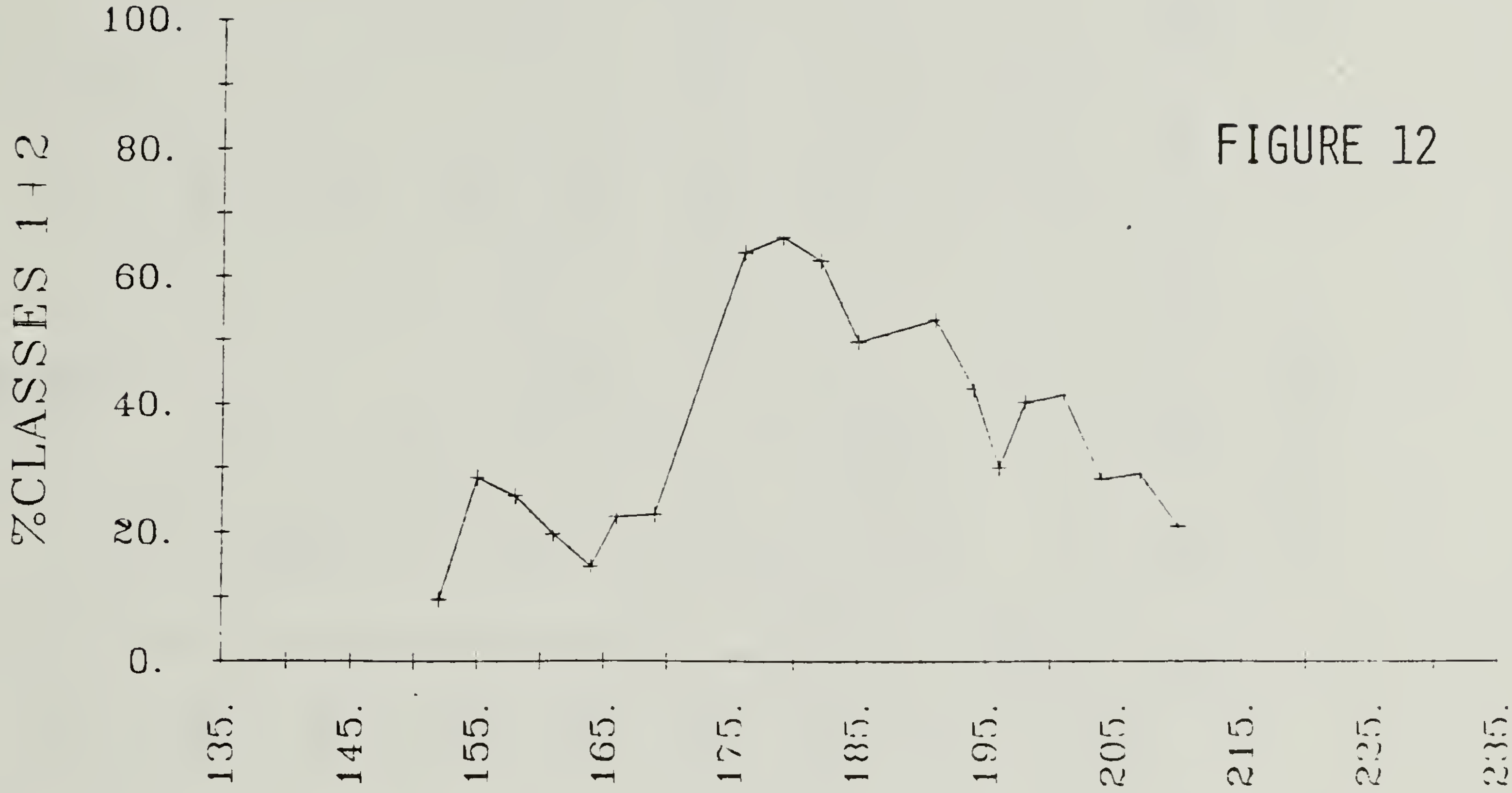
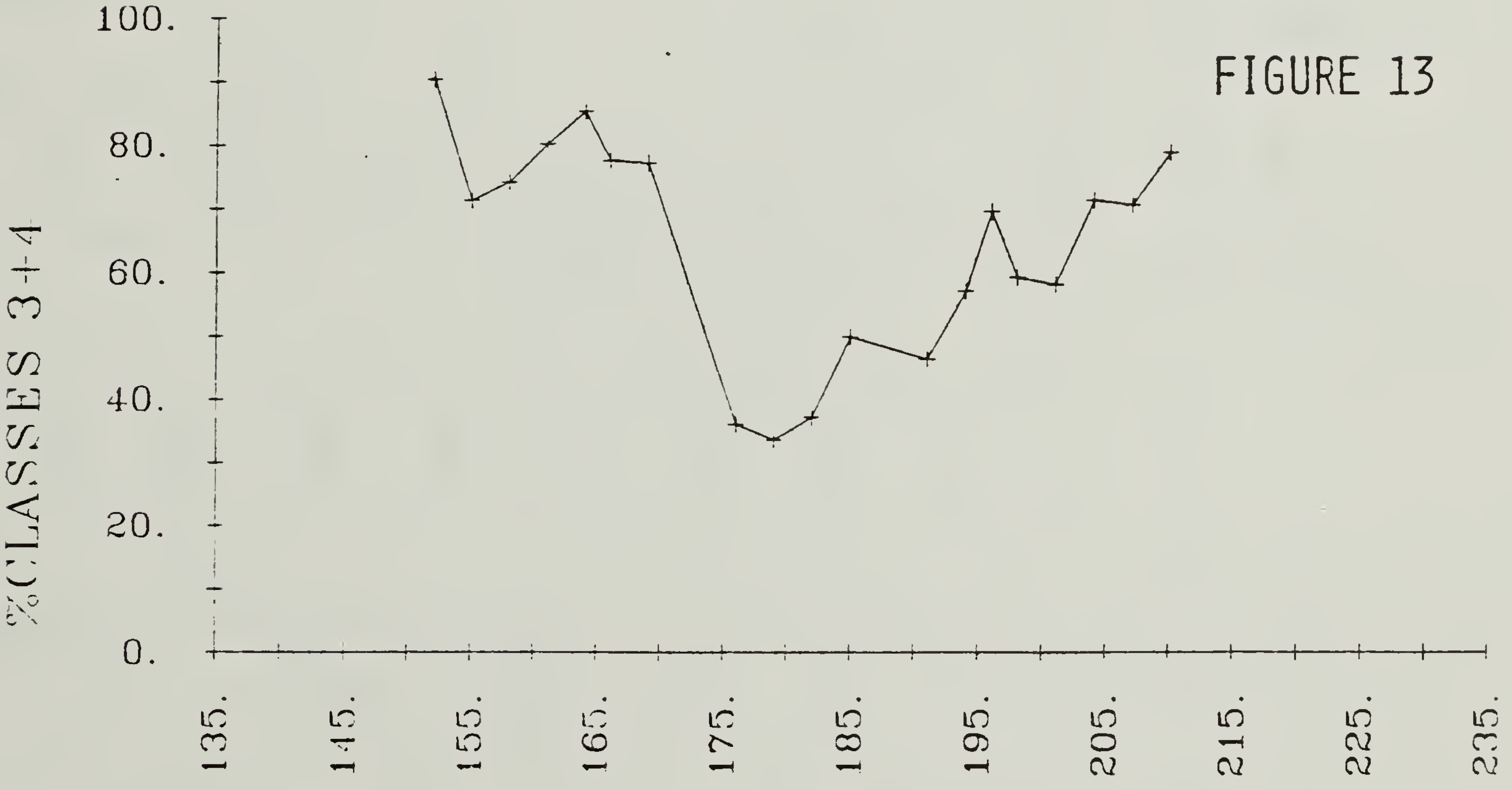


FIGURE 13



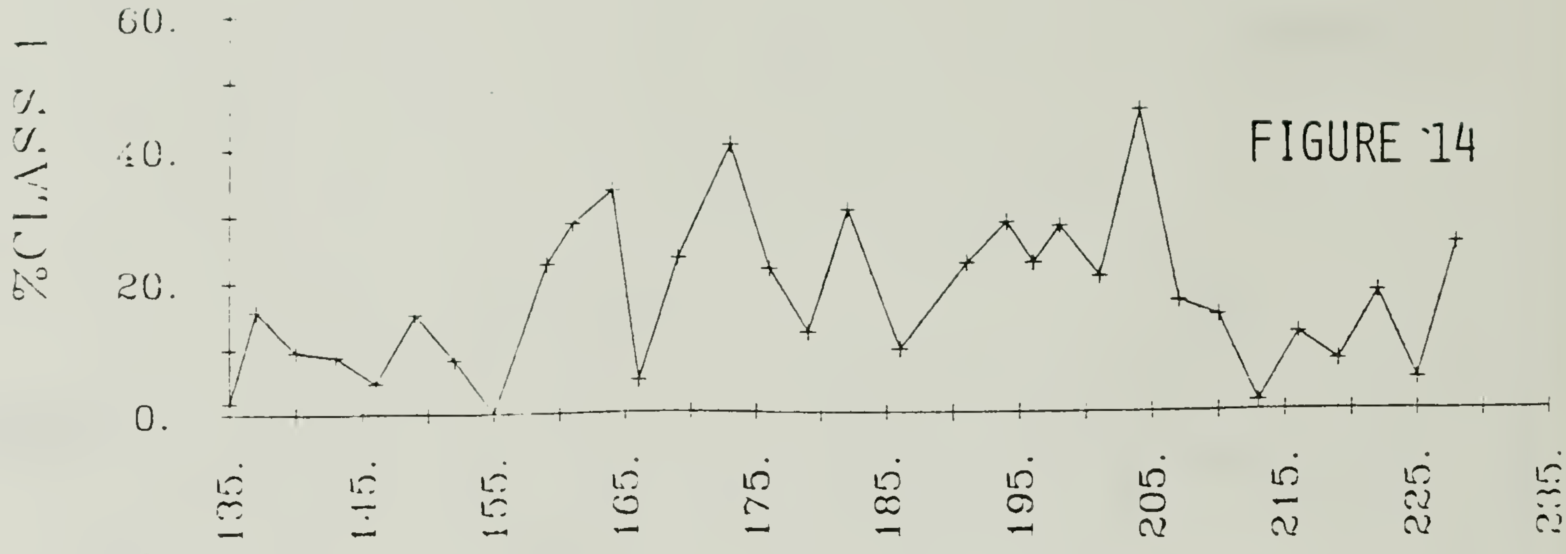


FIGURE 14

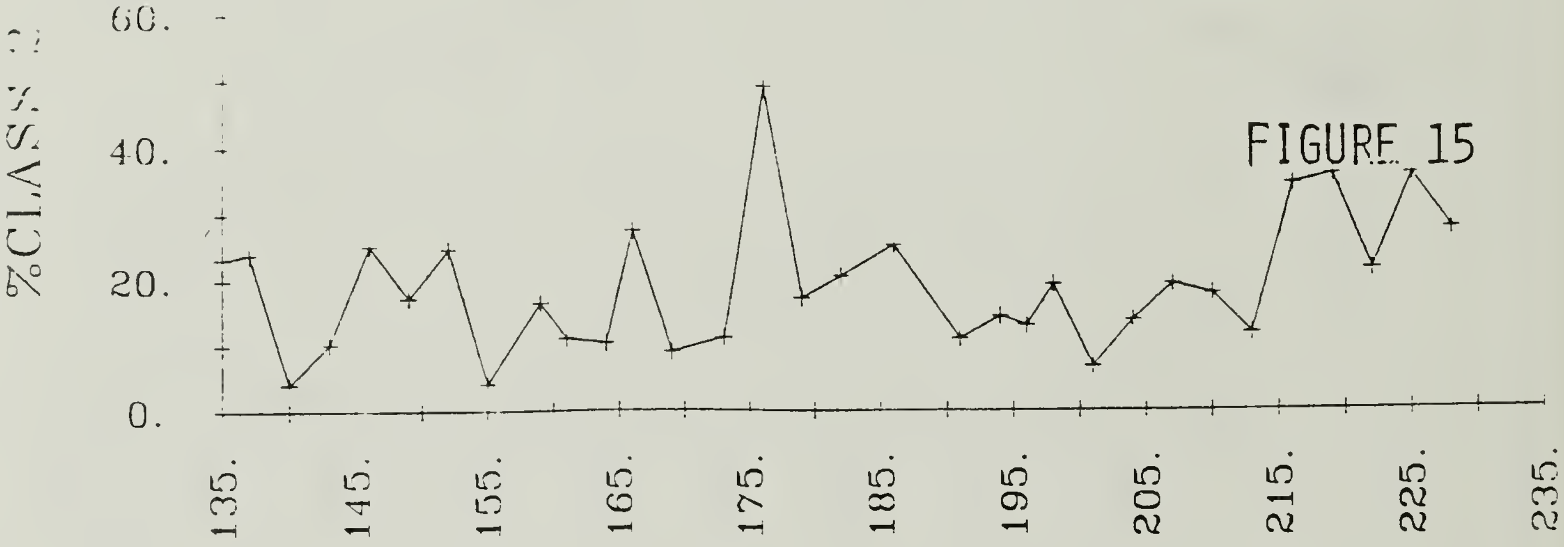


FIGURE 15

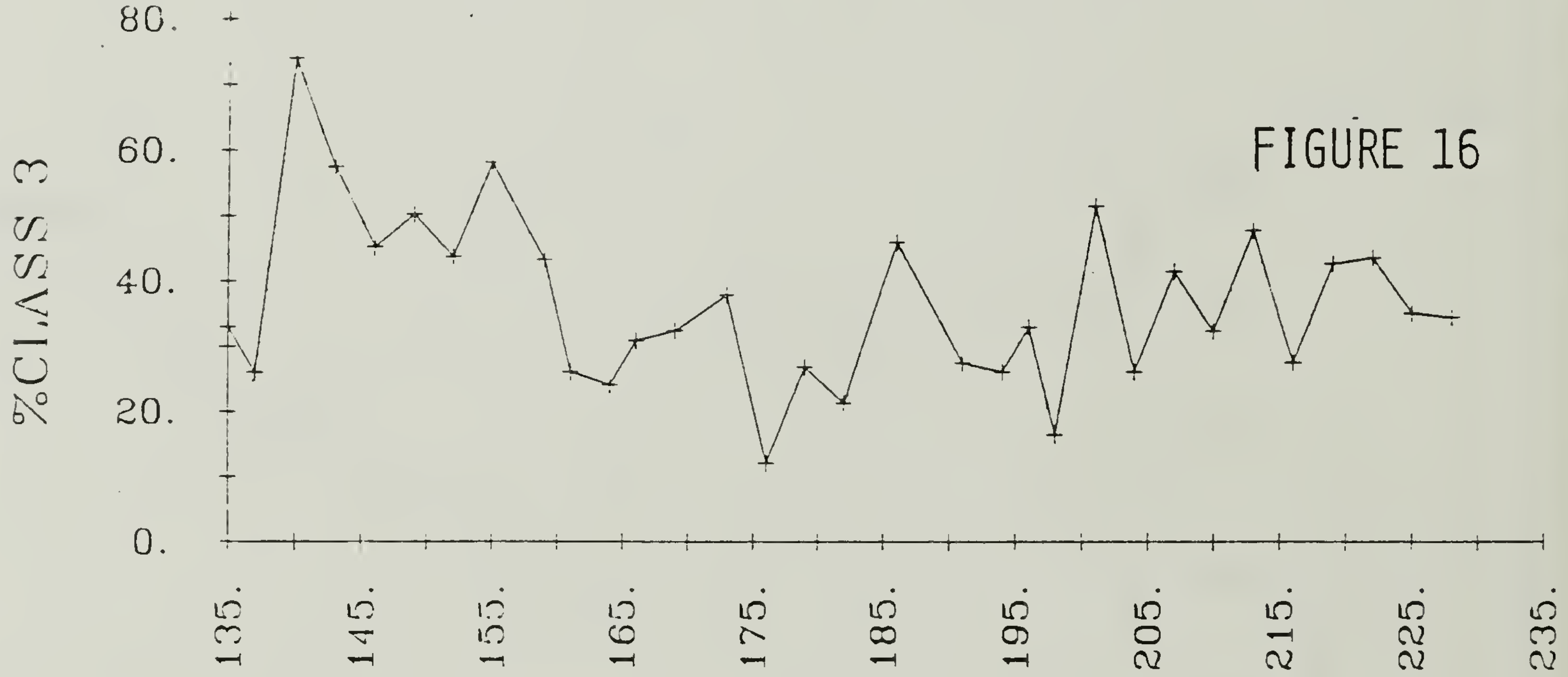


FIGURE 16

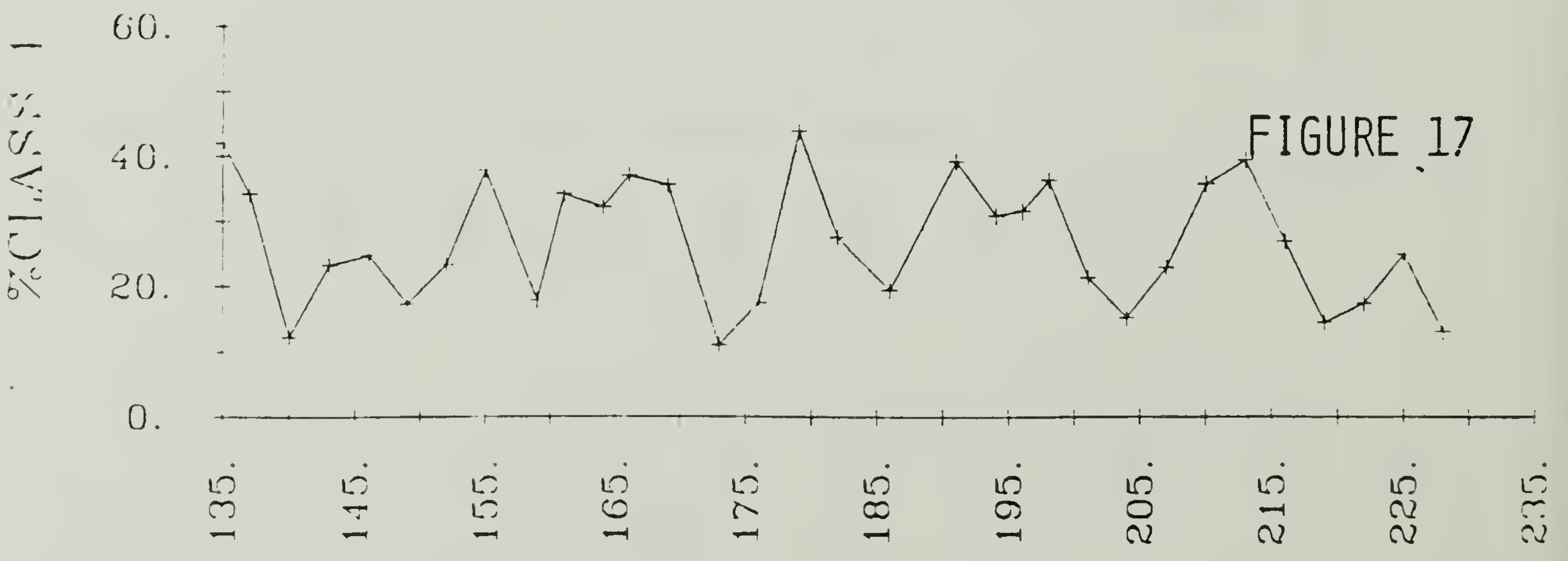


FIGURE 17

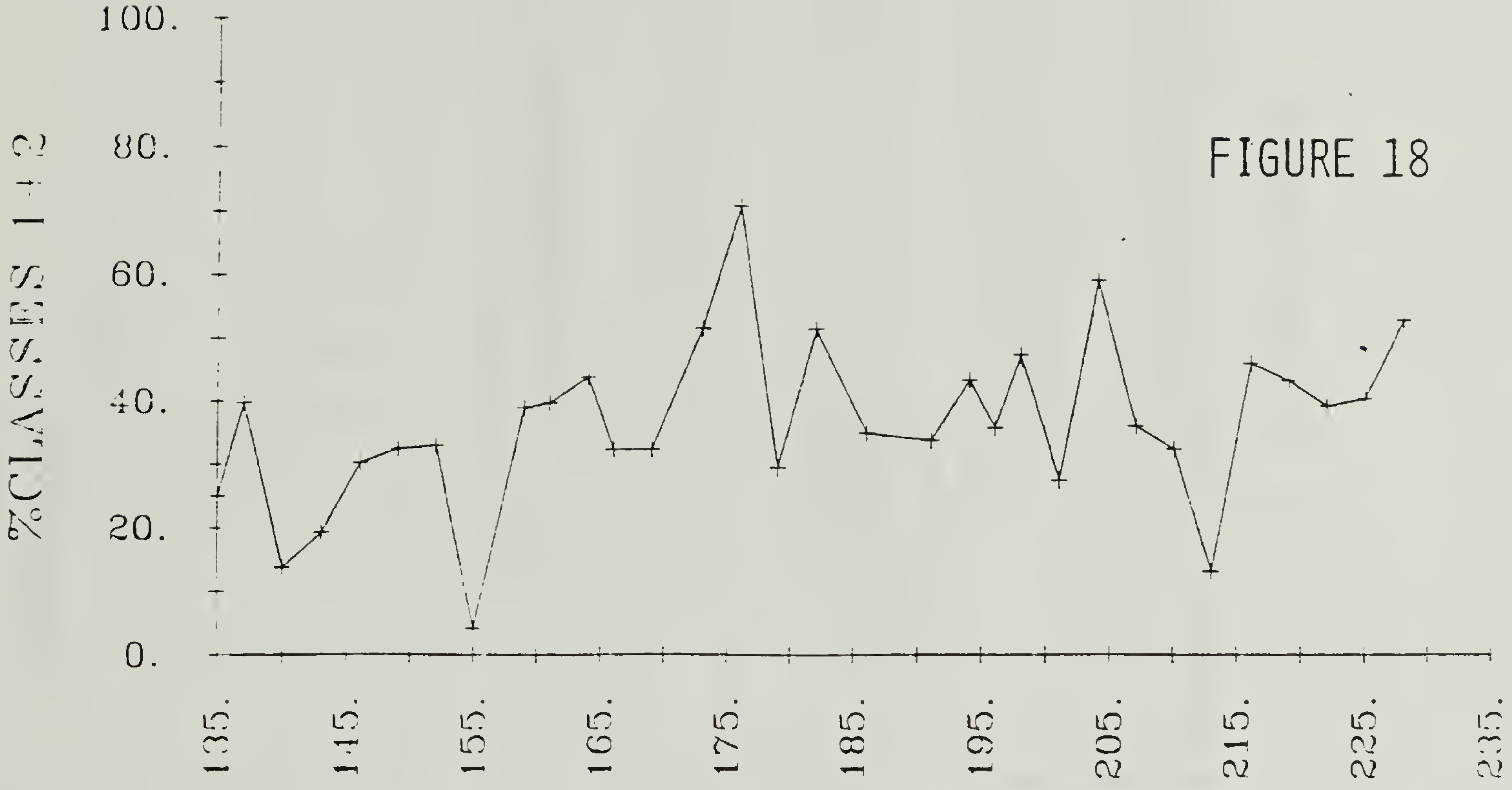


FIGURE 18

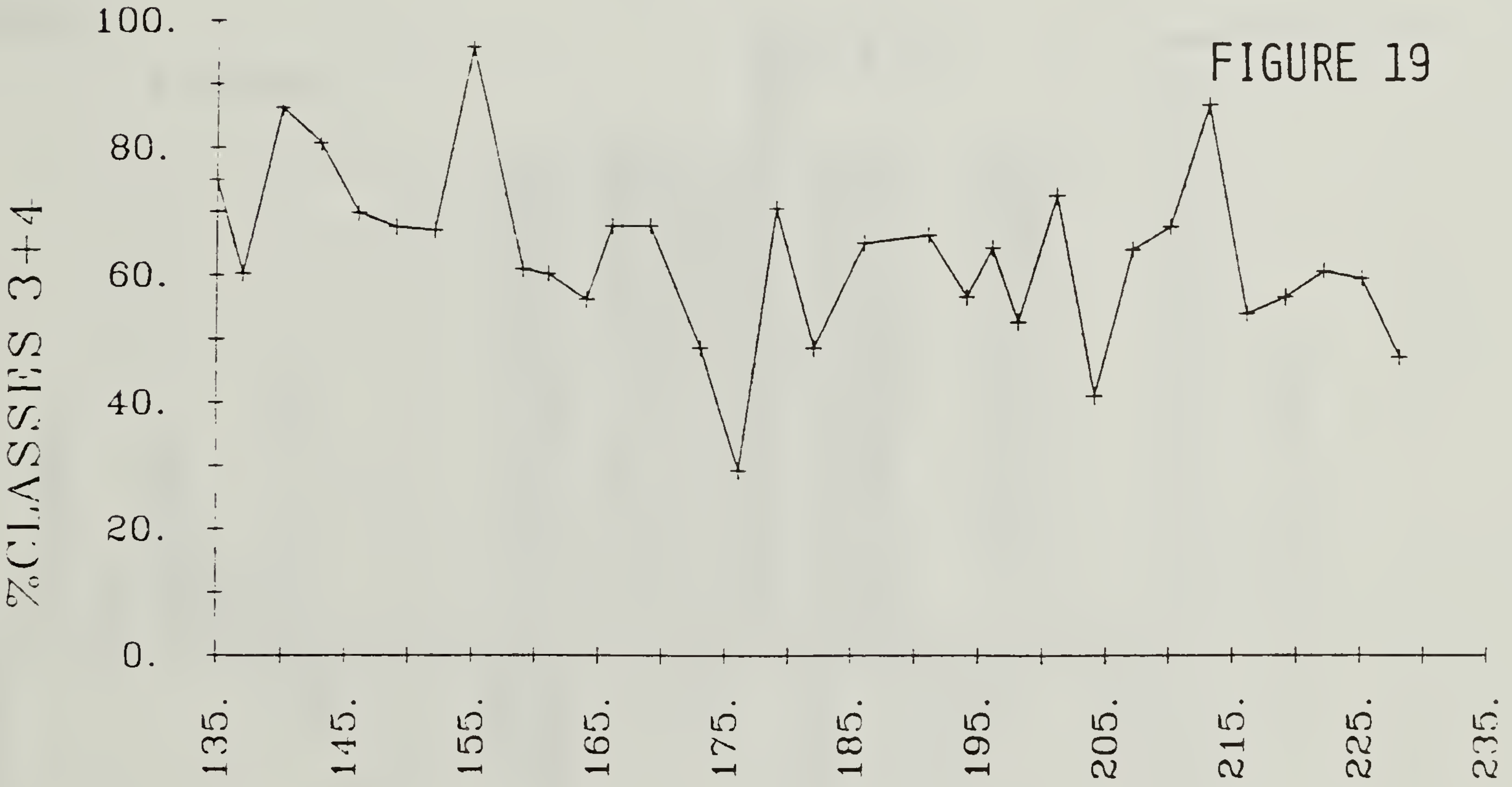


FIGURE 19

FIGURE 20

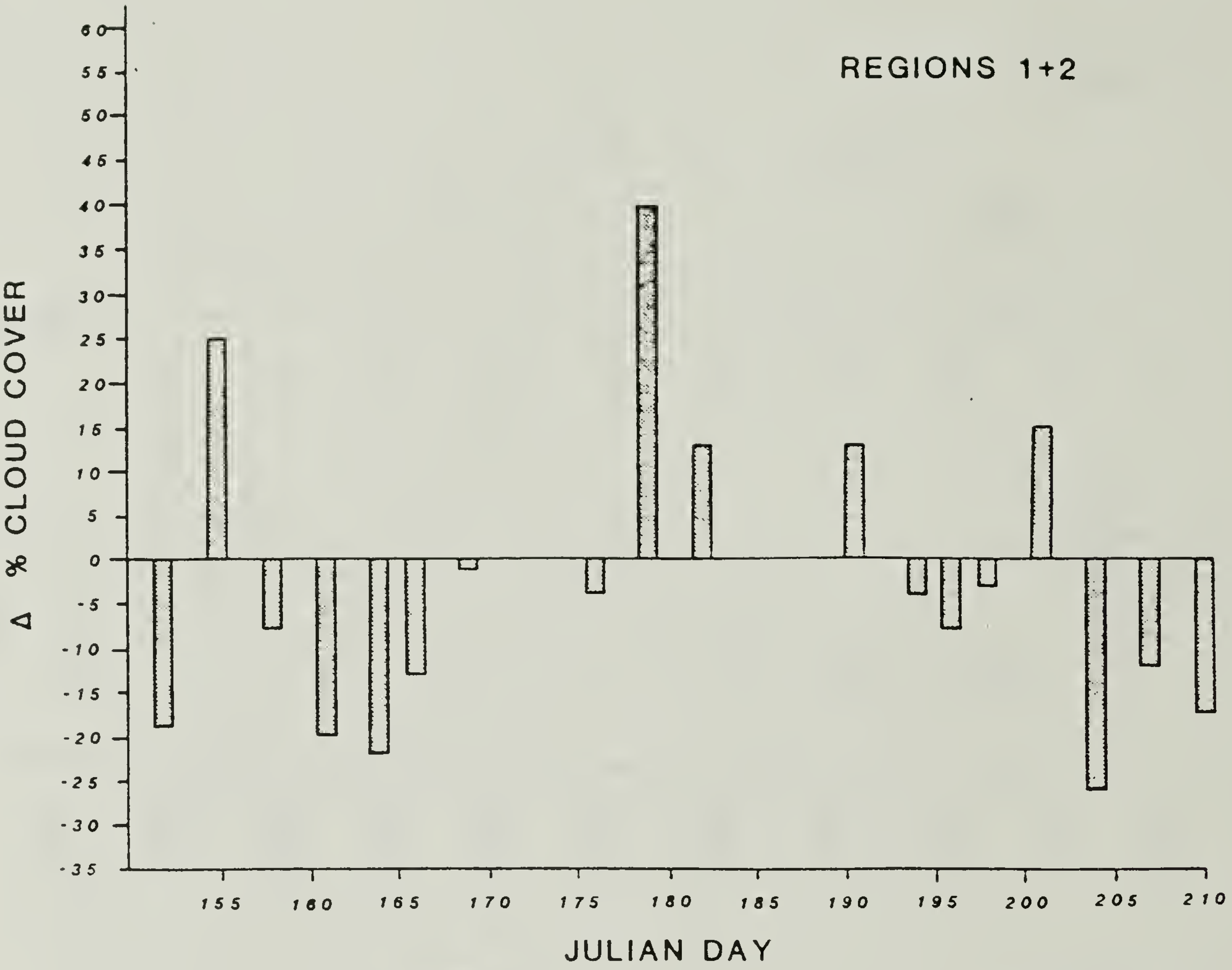


FIGURE 21

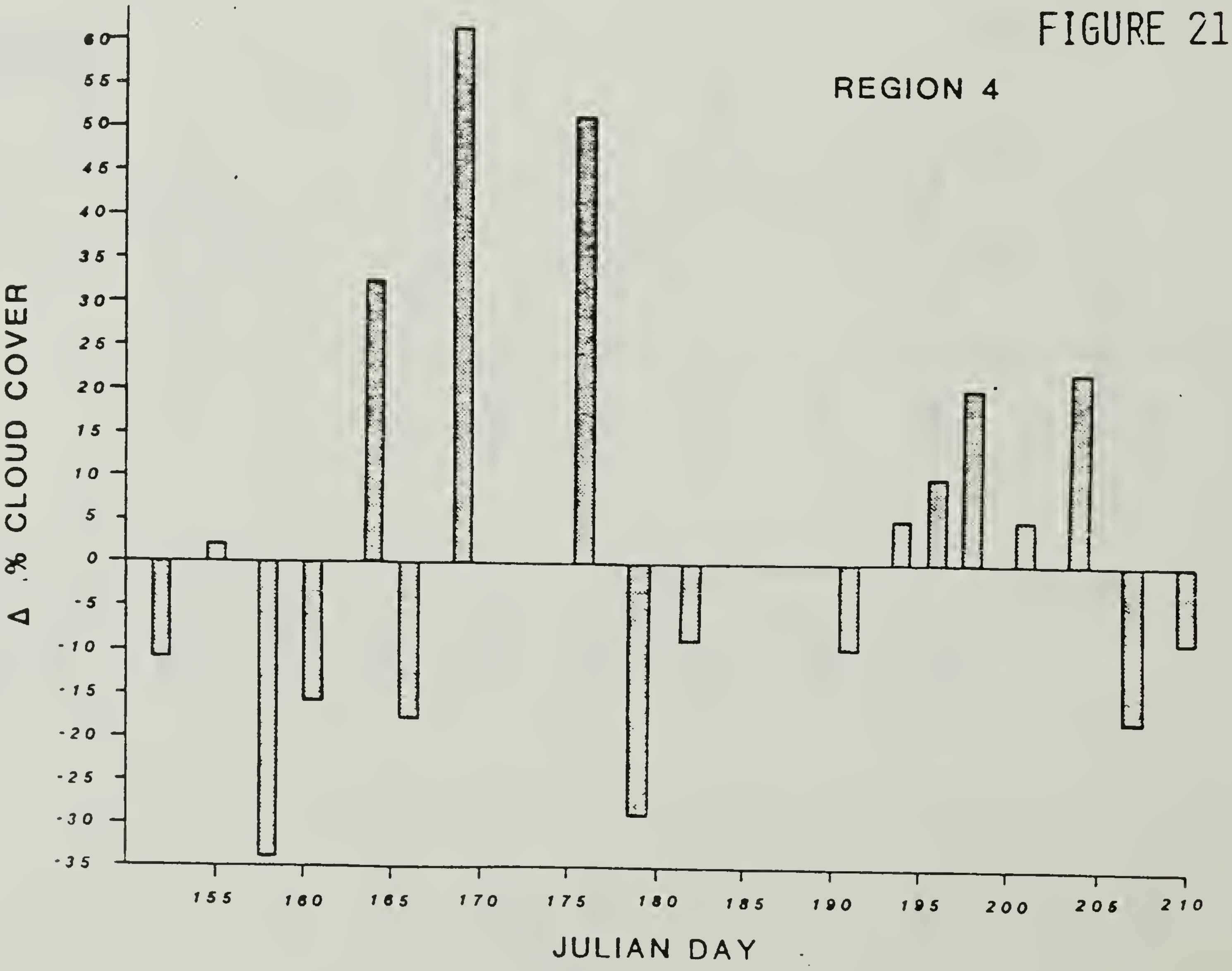


FIGURE 22

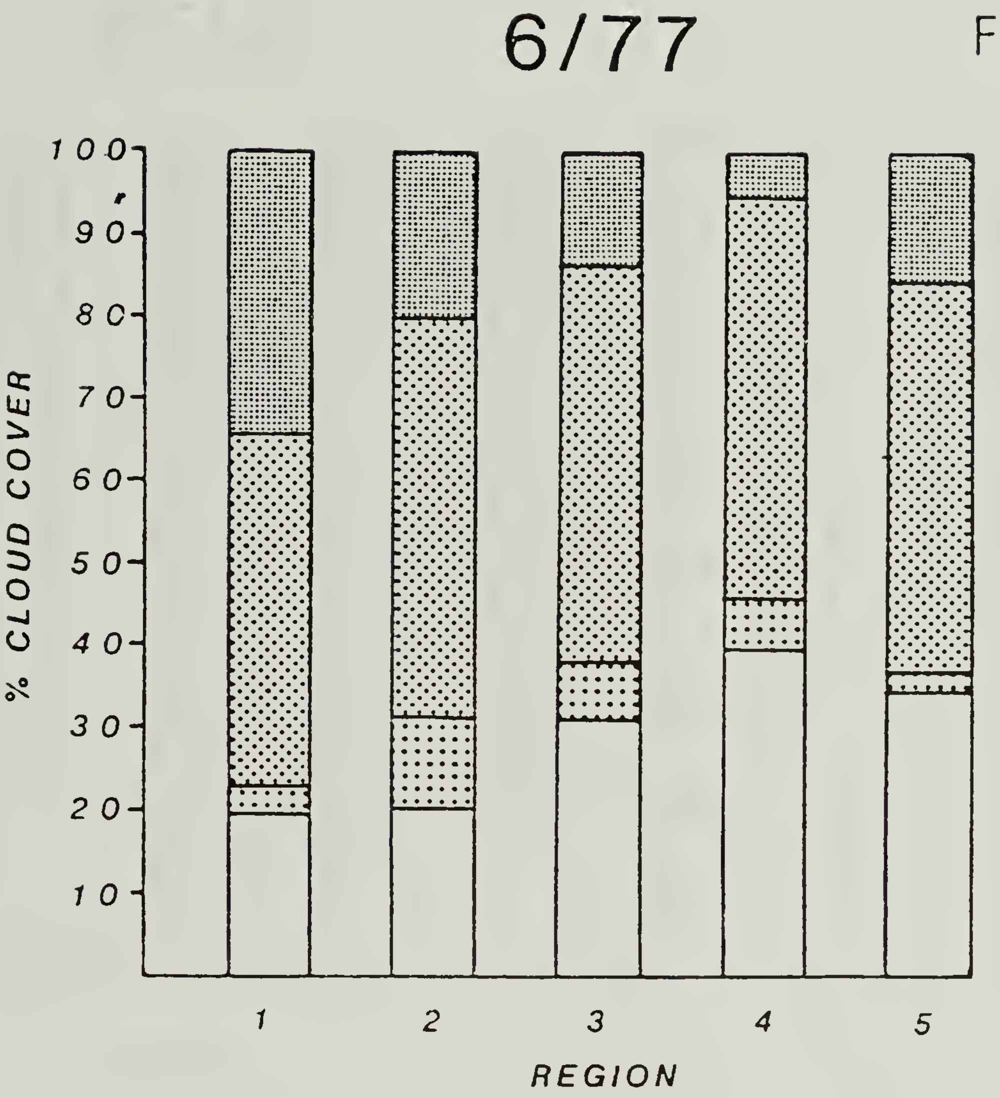


FIGURE 23

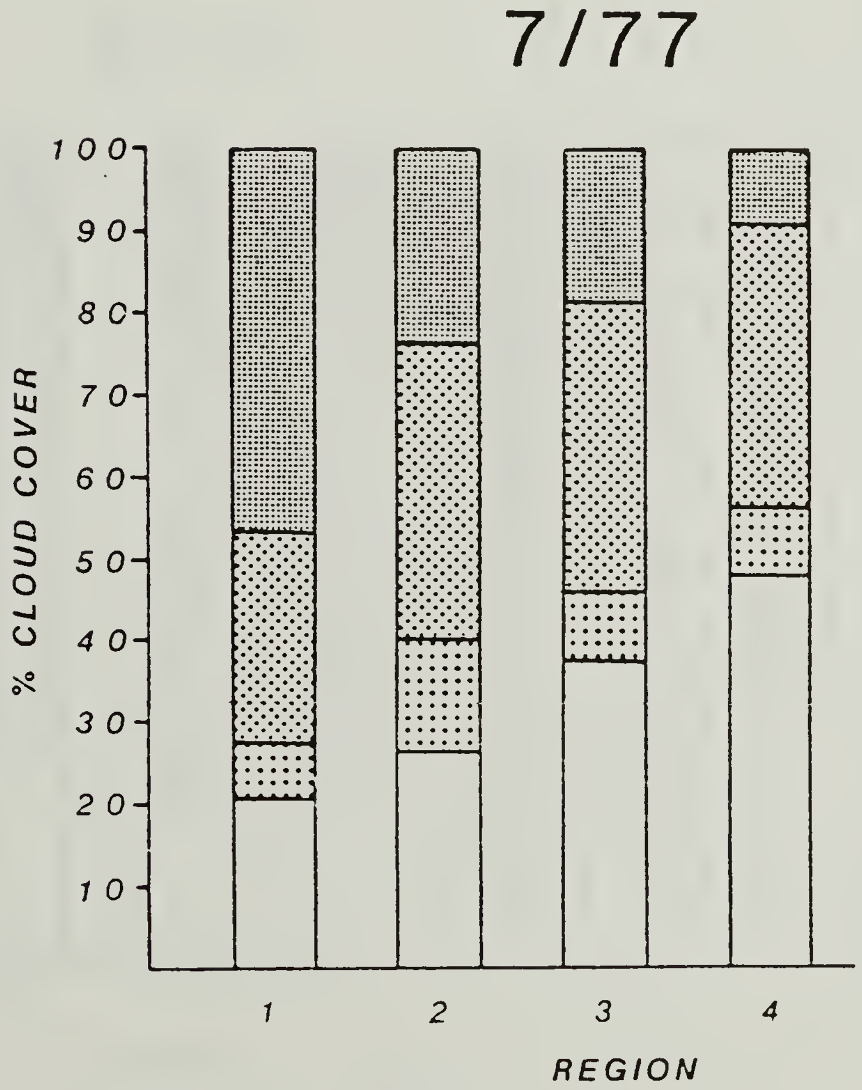


FIGURE 24

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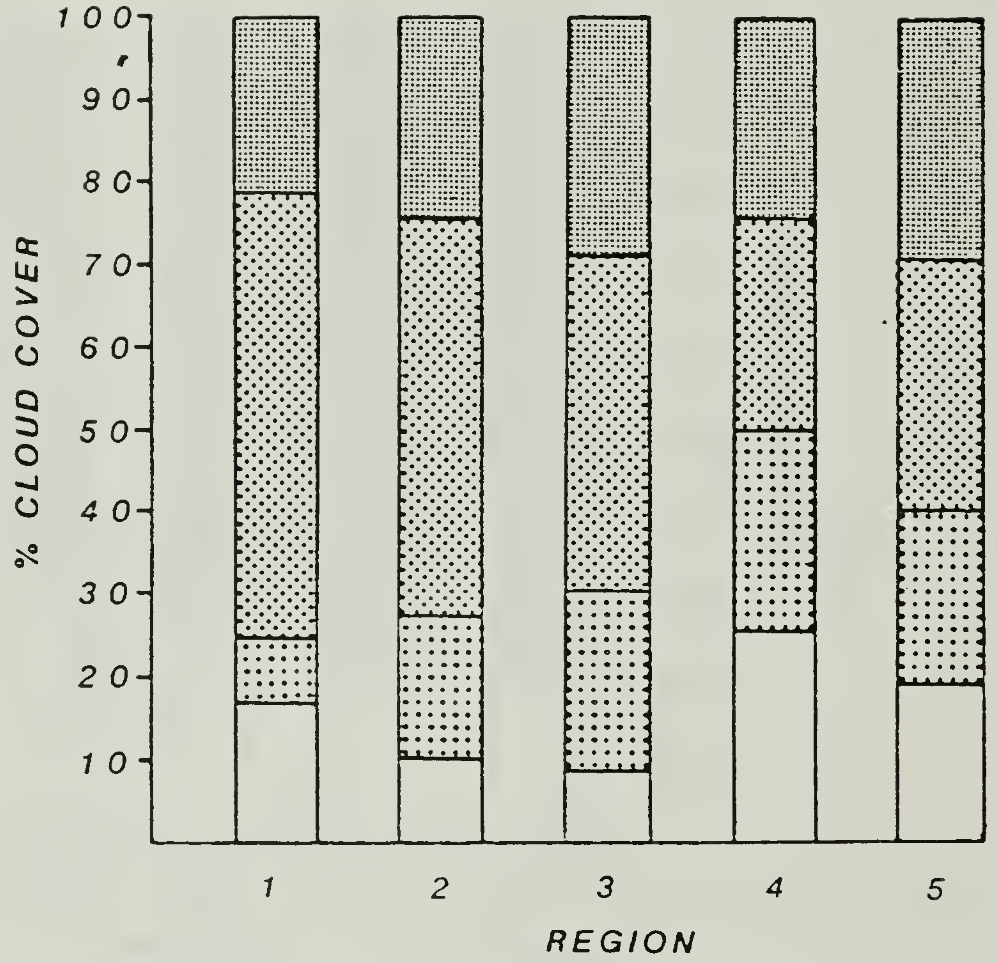

FIGURE 25

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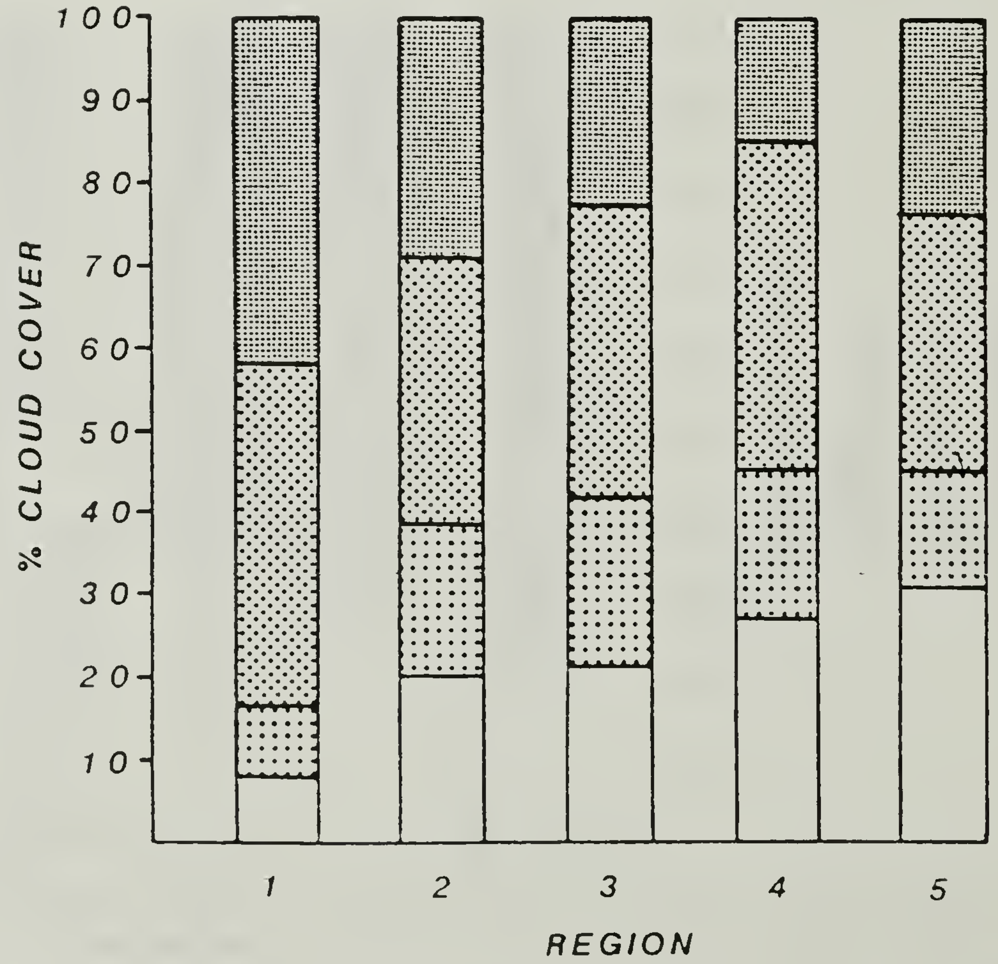

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FIGURE 26

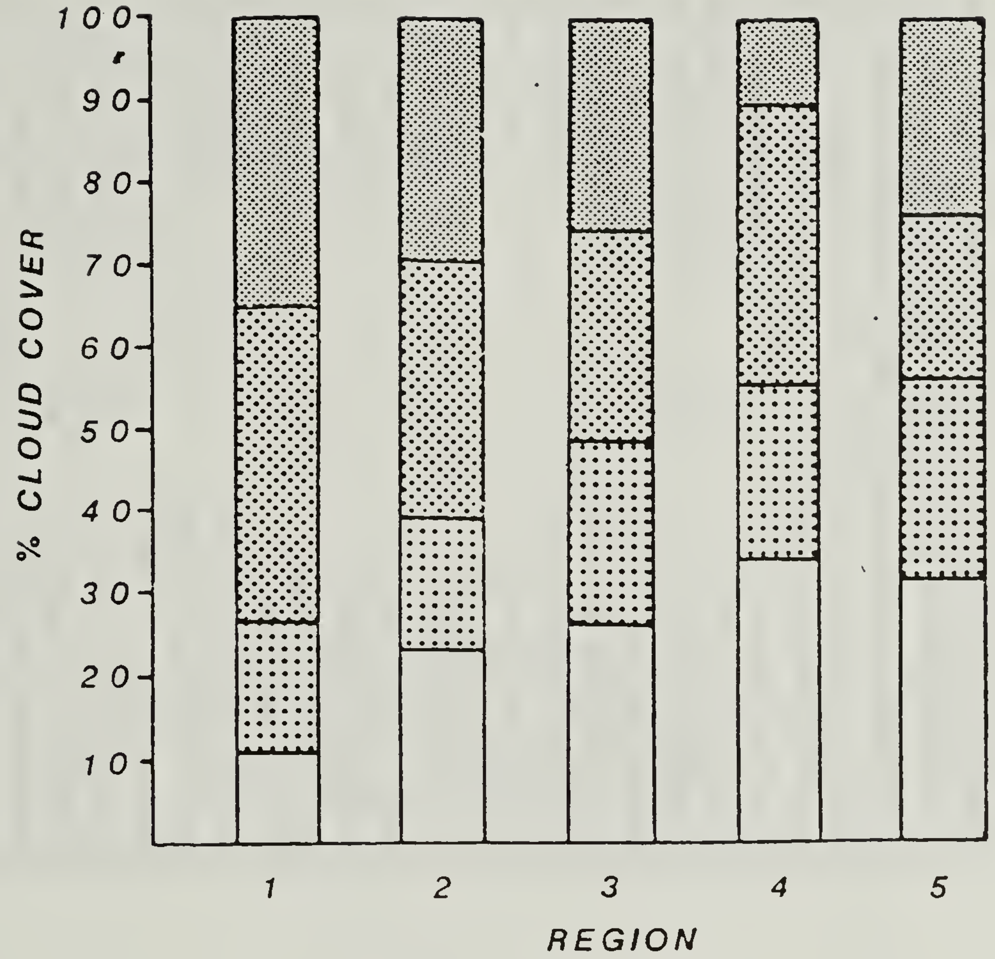

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FIGURE 27

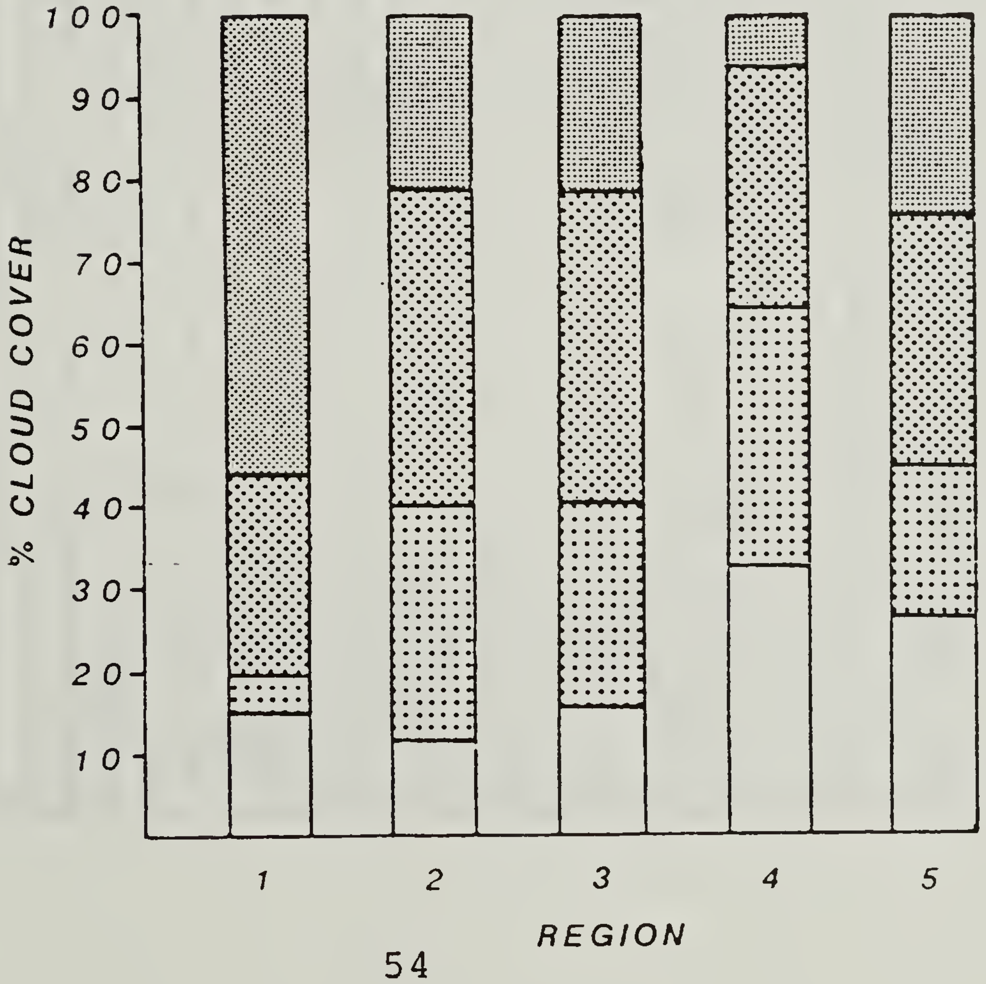


FIGURE 28

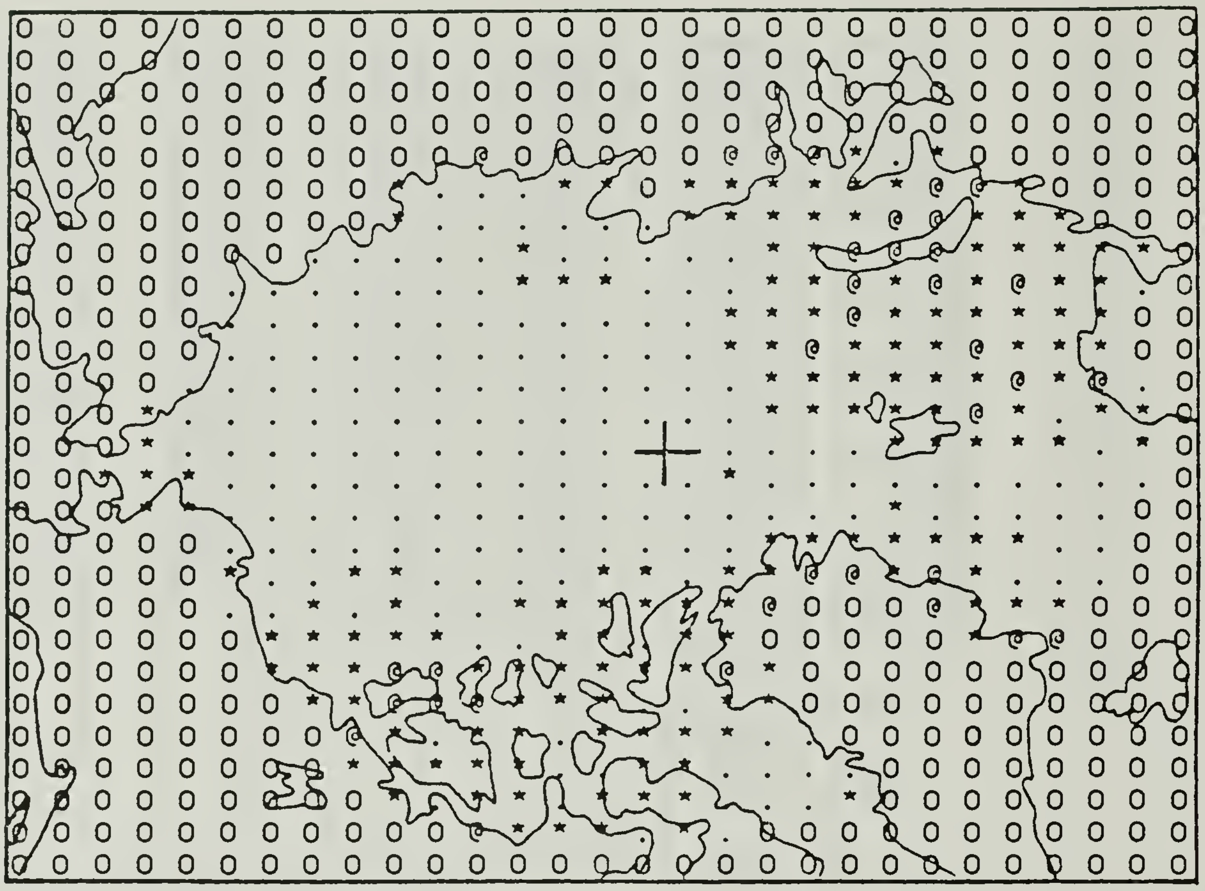


FIGURE 29

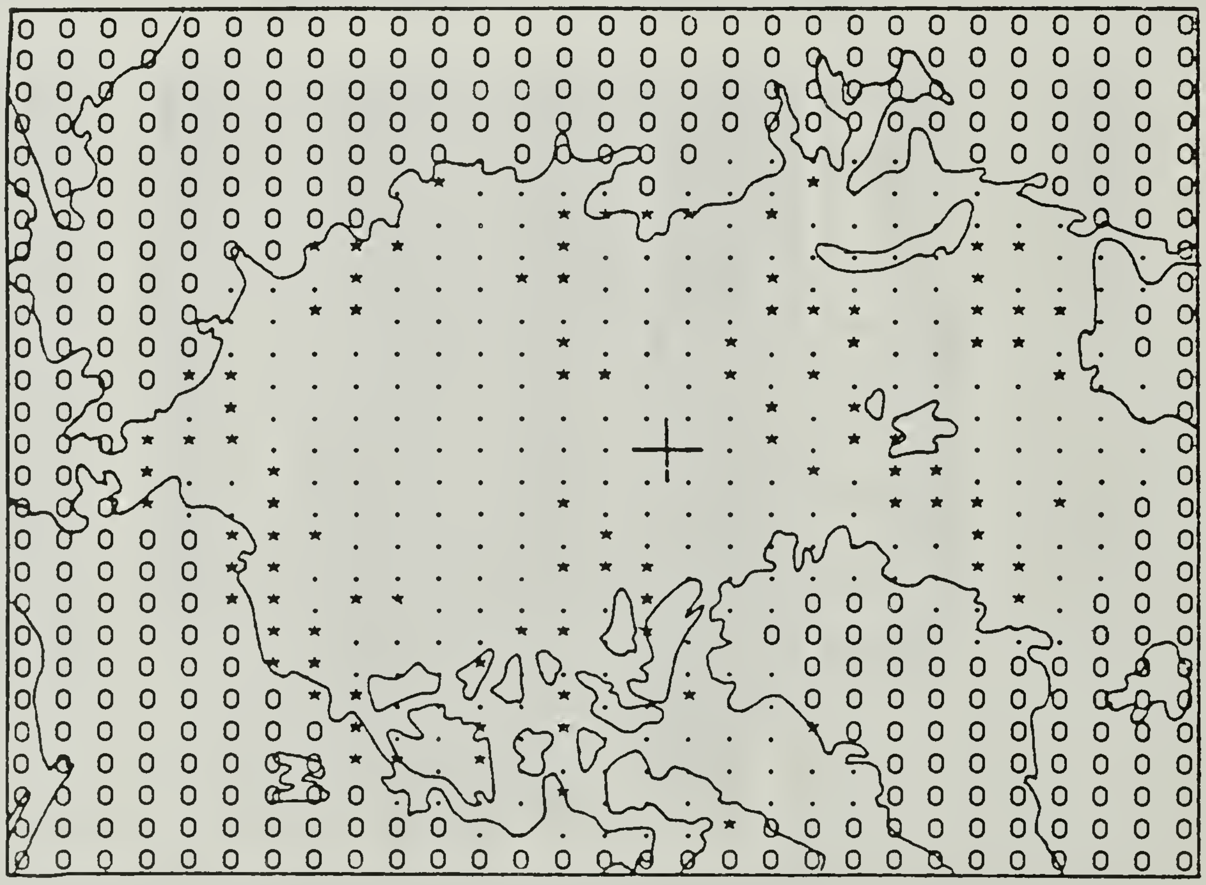
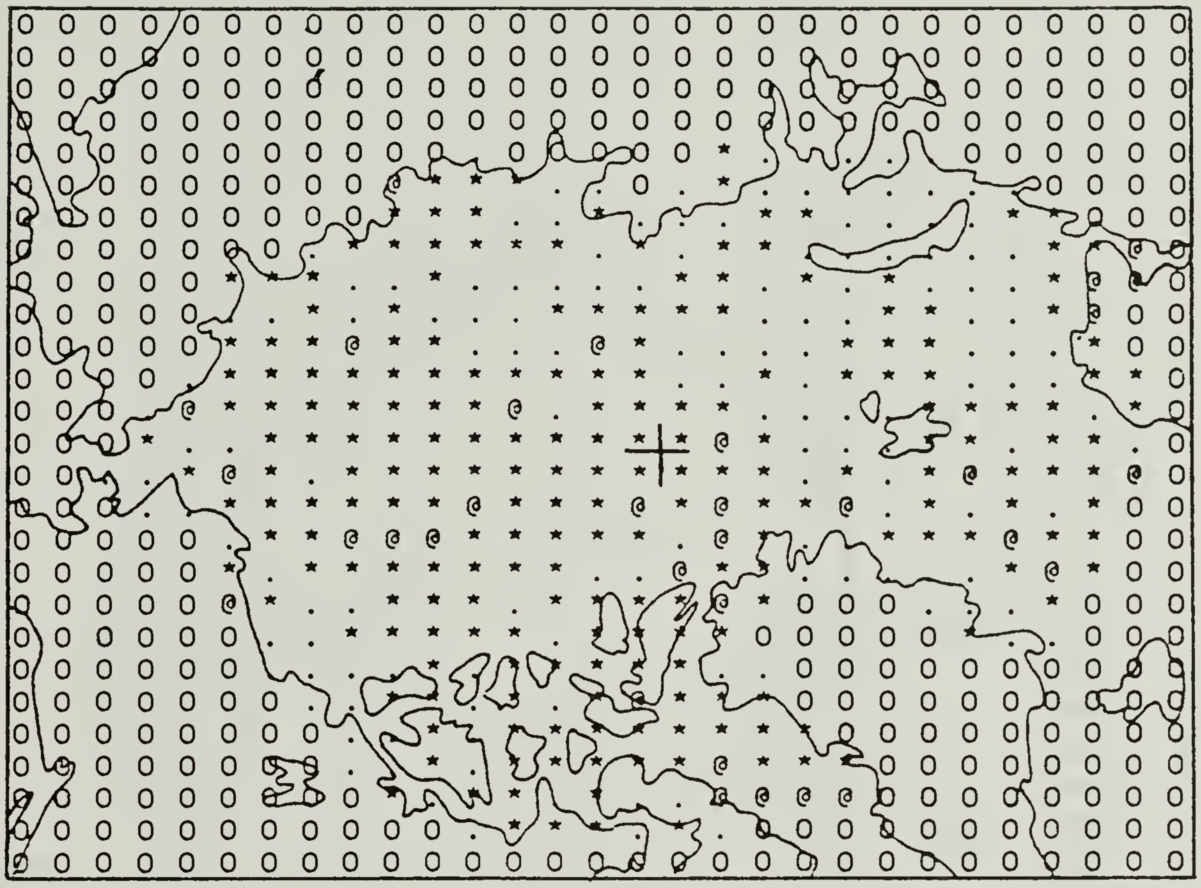


FIGURE 30



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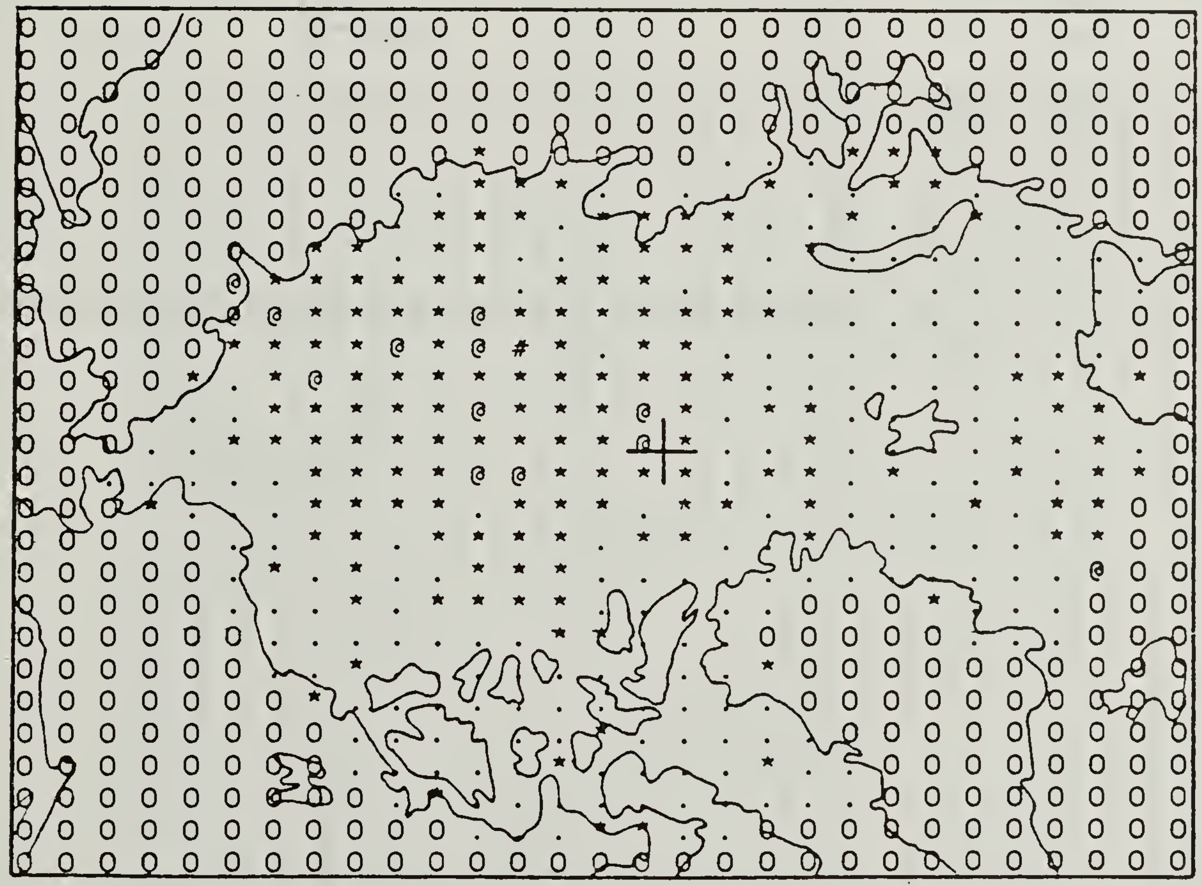


FIGURE 32

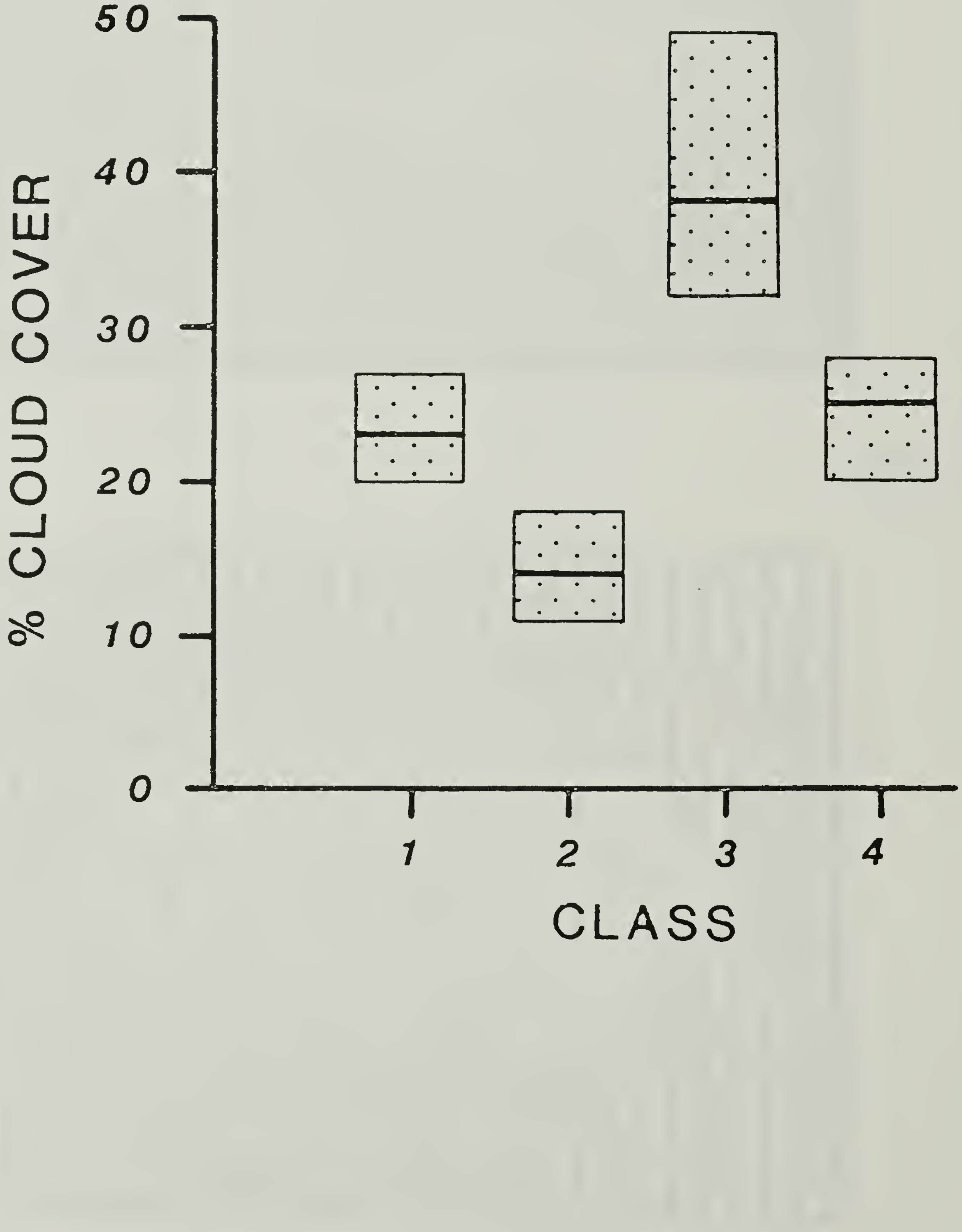


FIGURE 33

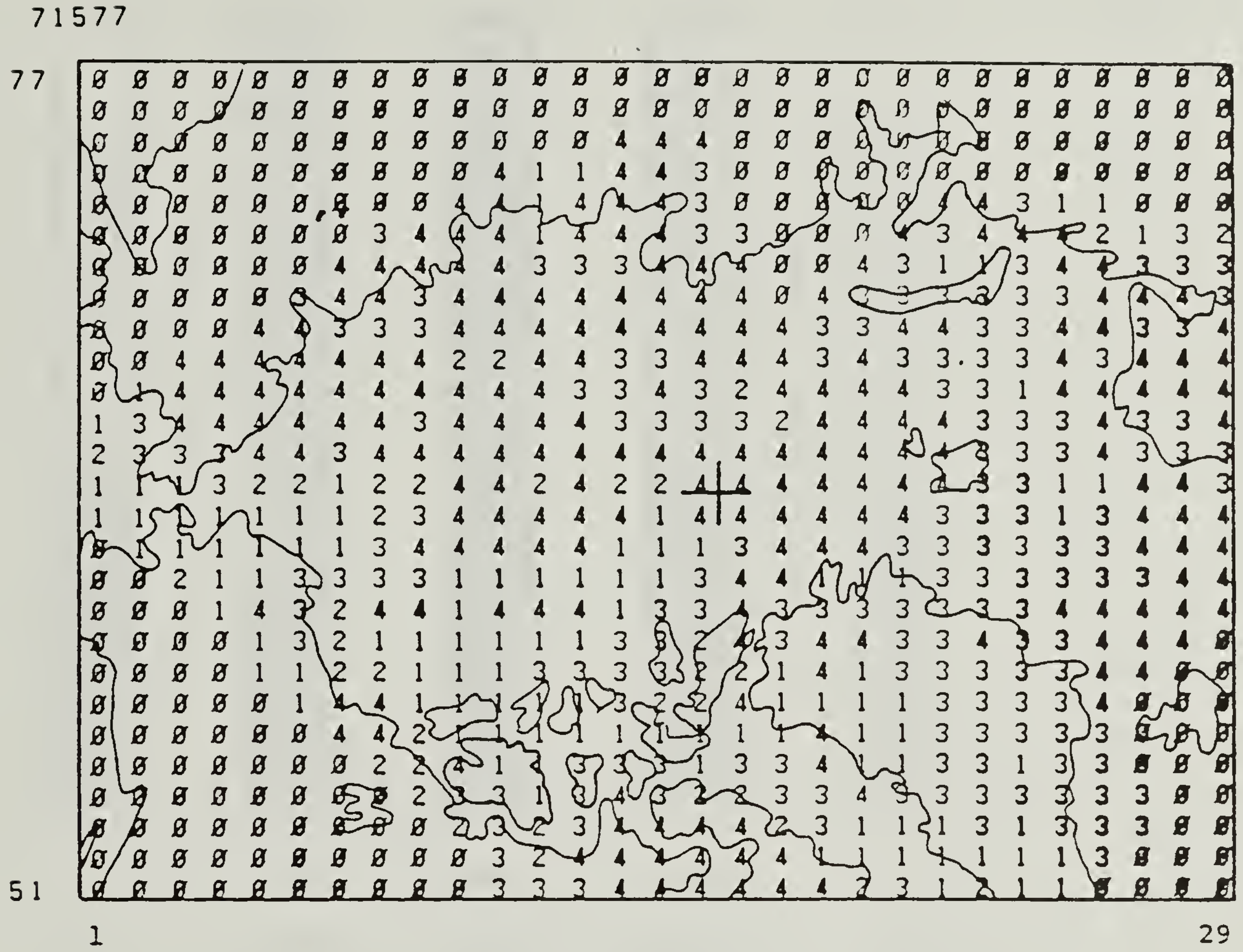
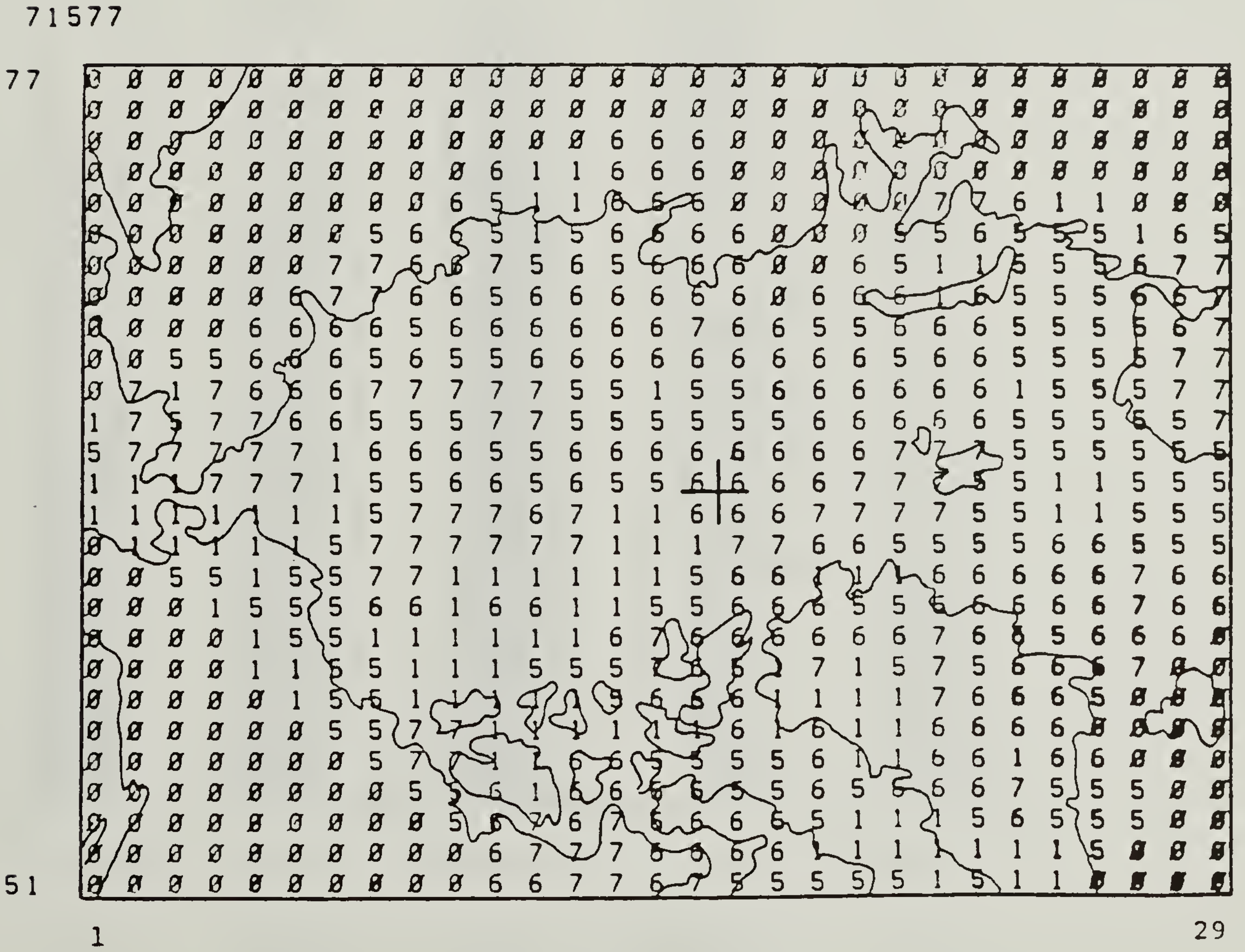
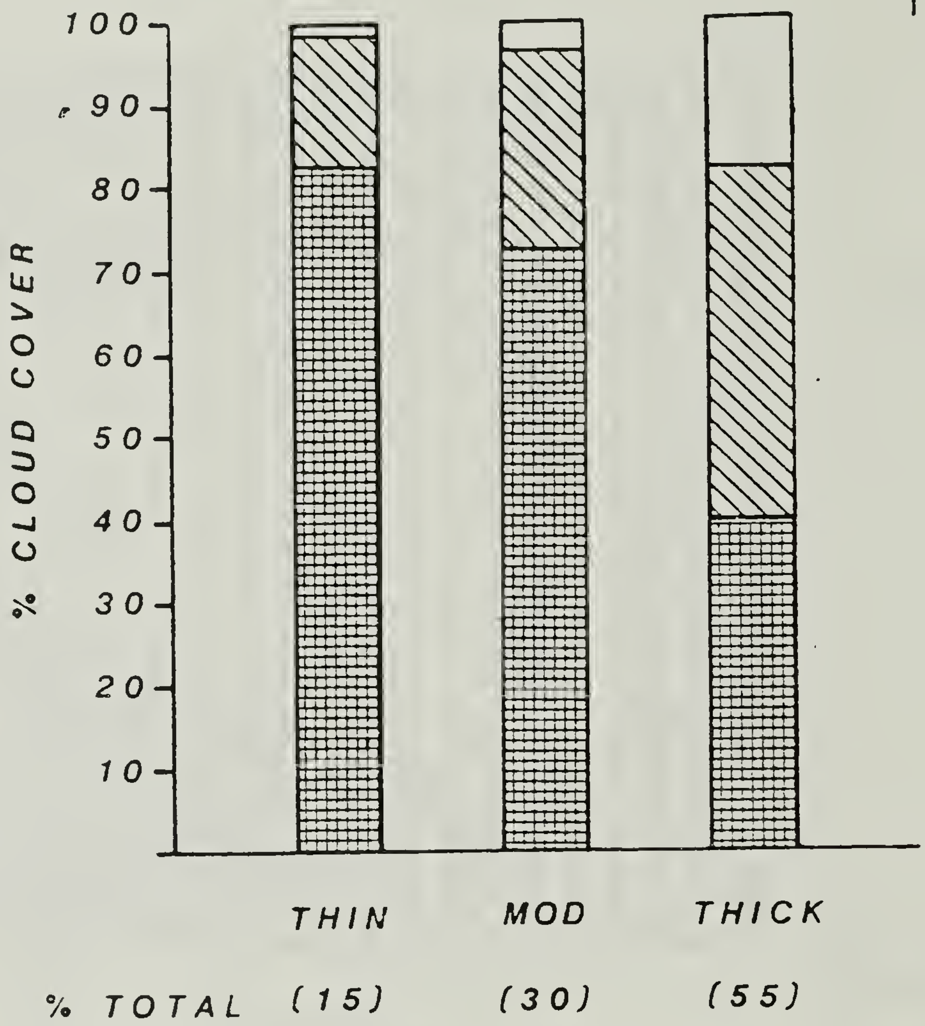


FIGURE 34



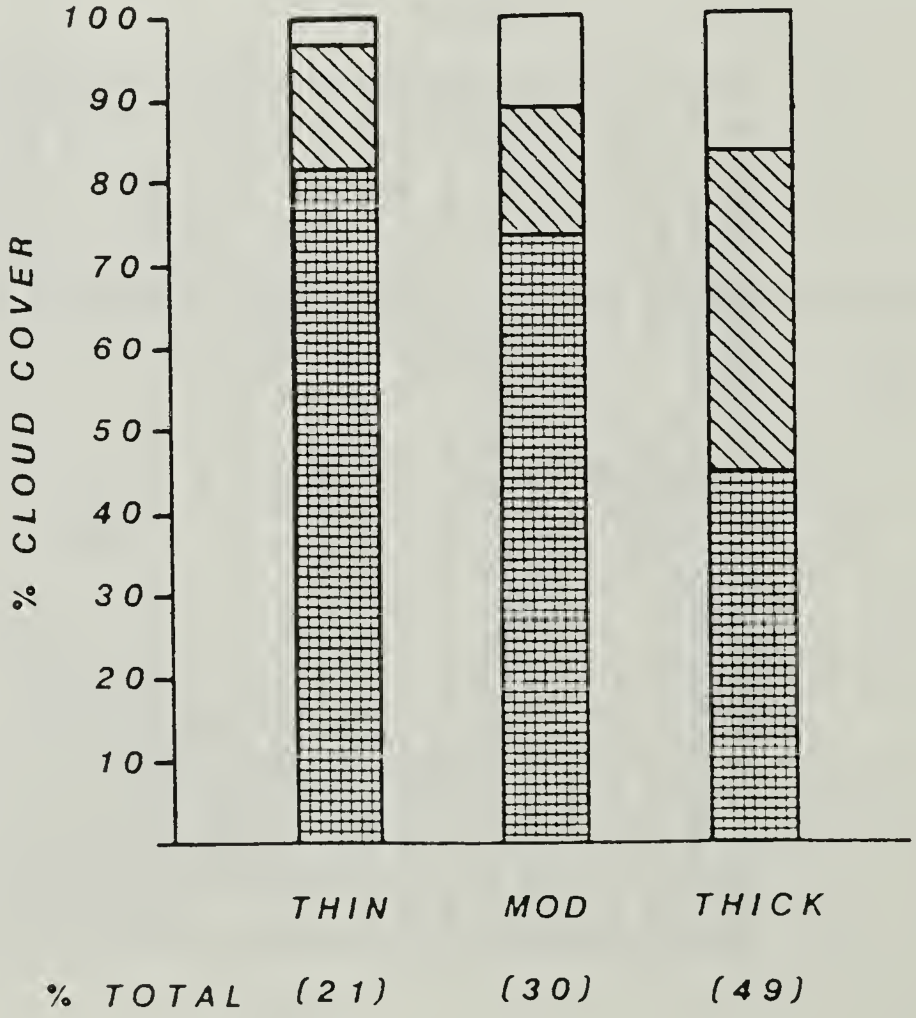
REGIONS 1 + 2

FIGURE 35



REGION 3

FIGURE 36



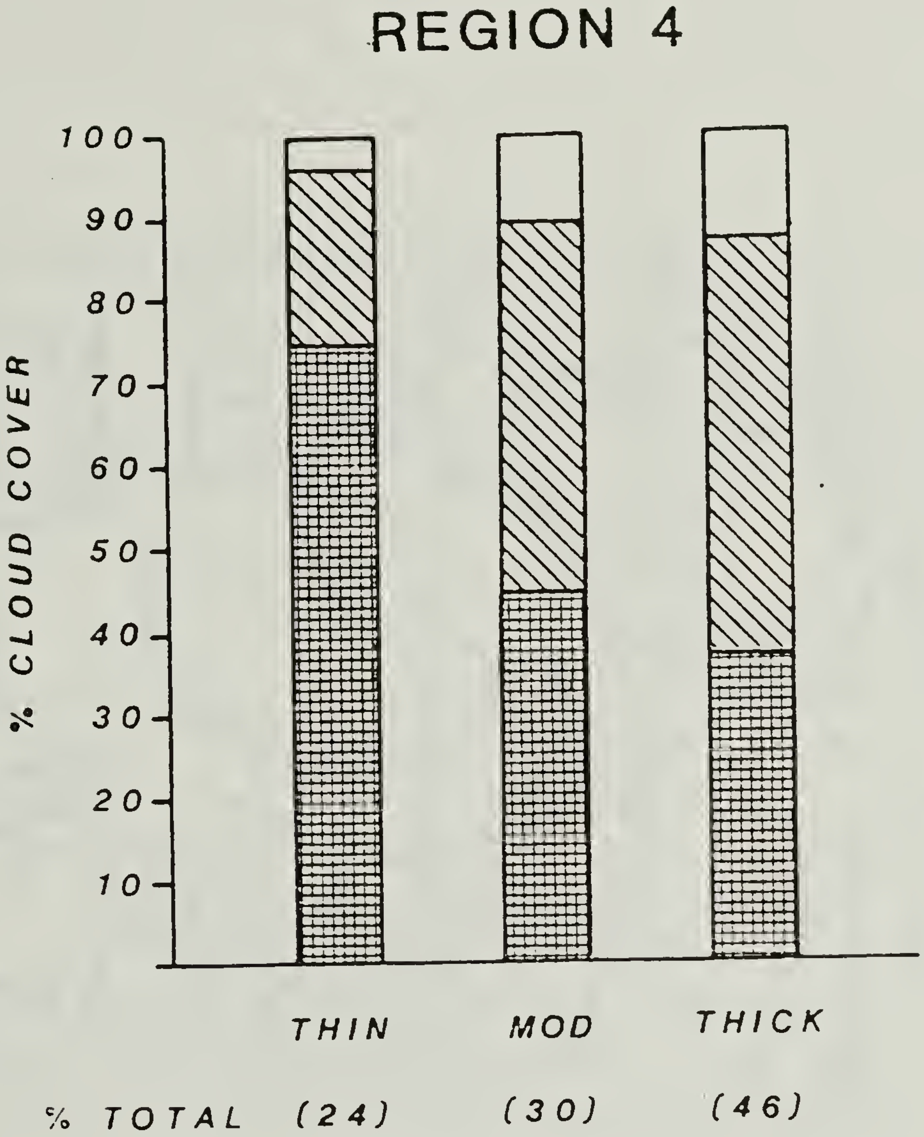


FIGURE 37

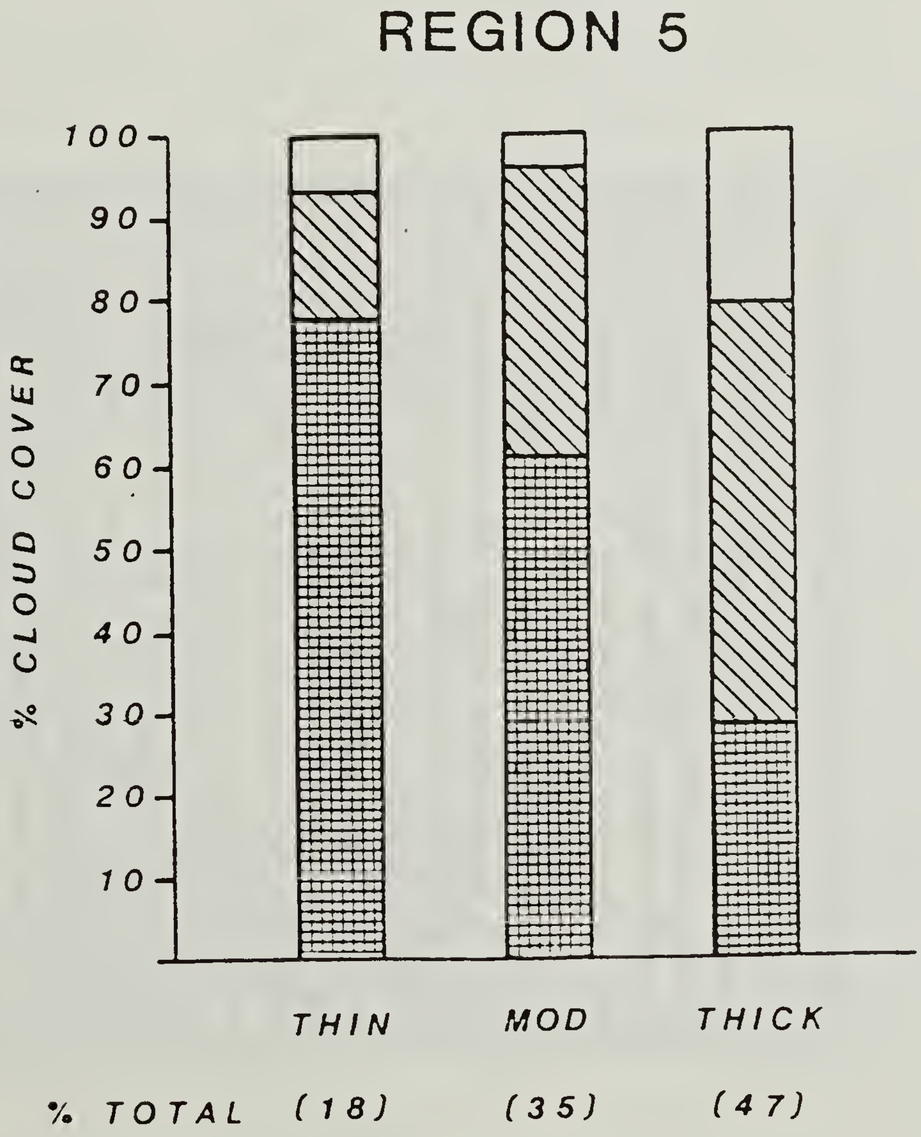


FIGURE 38

FIGURE 39

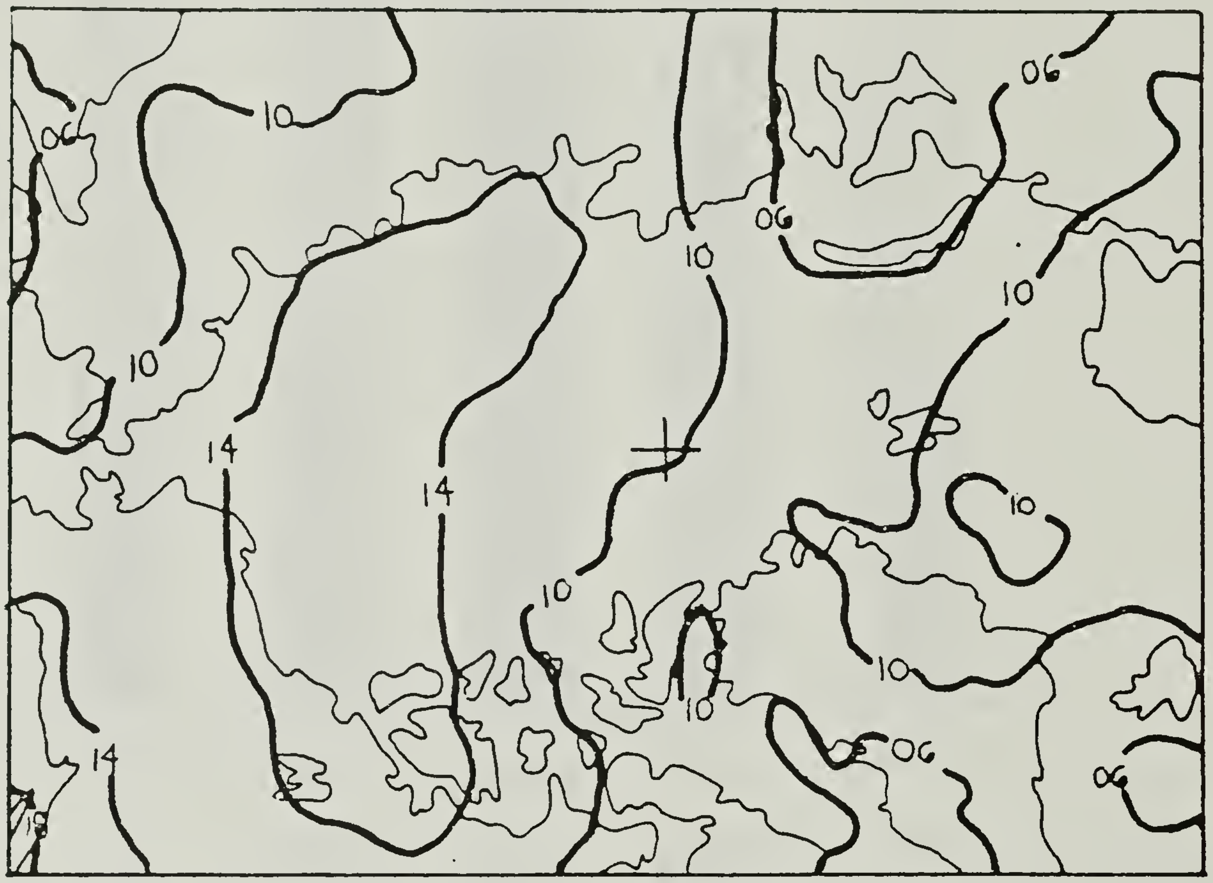


FIGURE 40

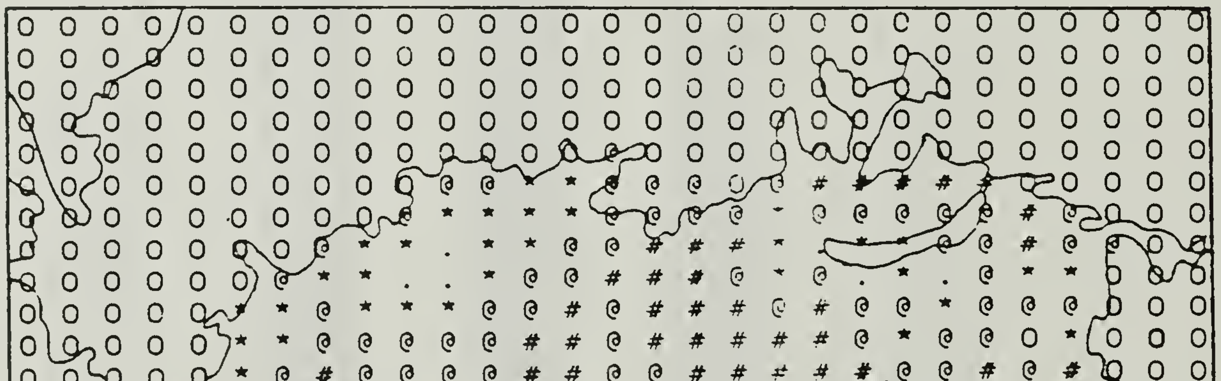


FIGURE 41

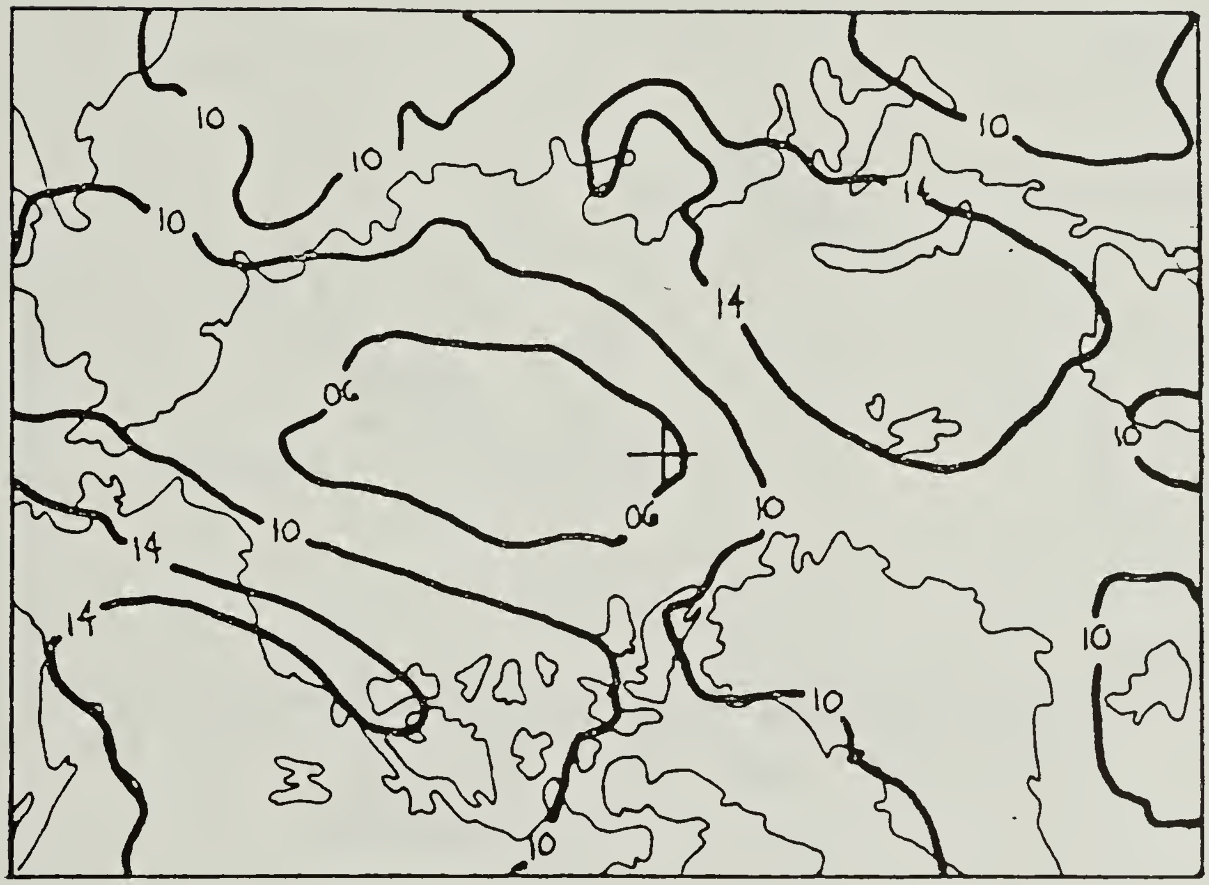


FIGURE 42

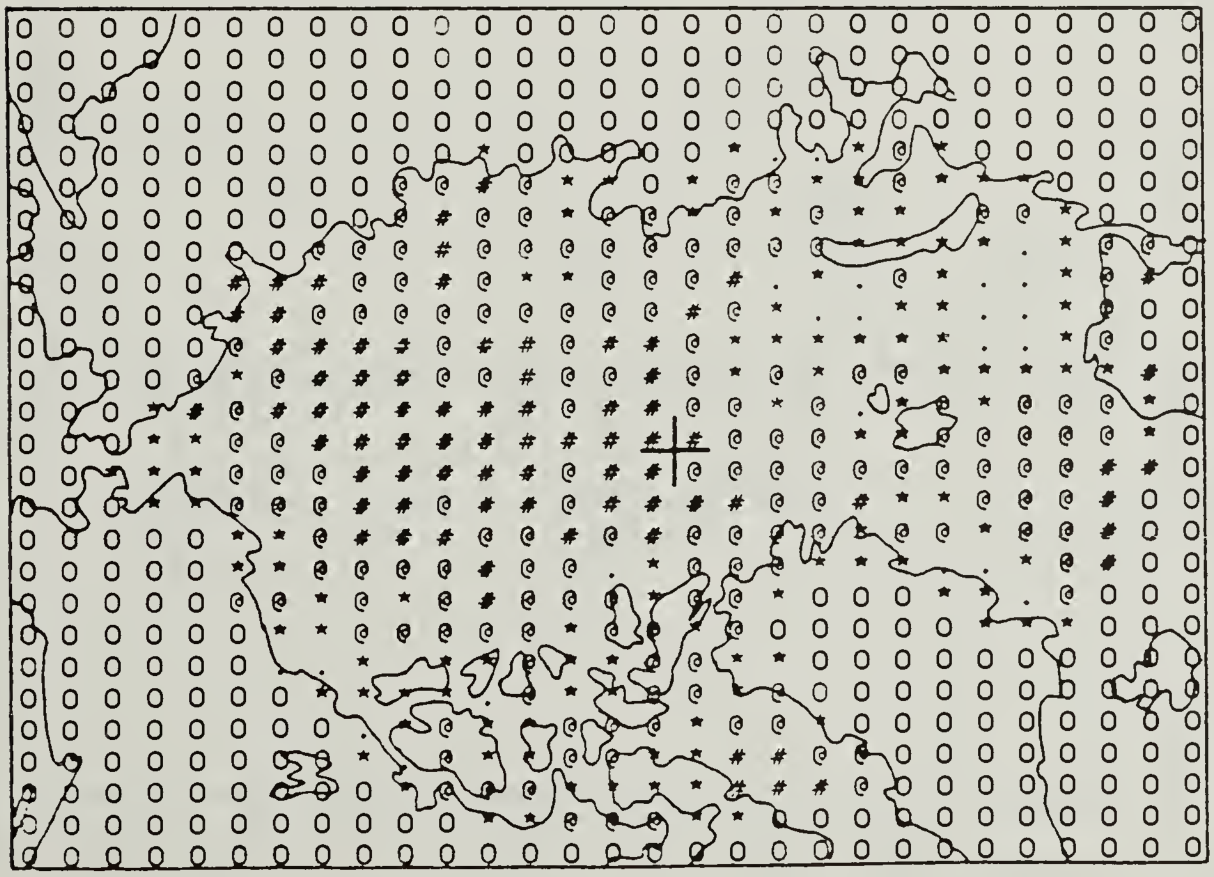


FIGURE 43

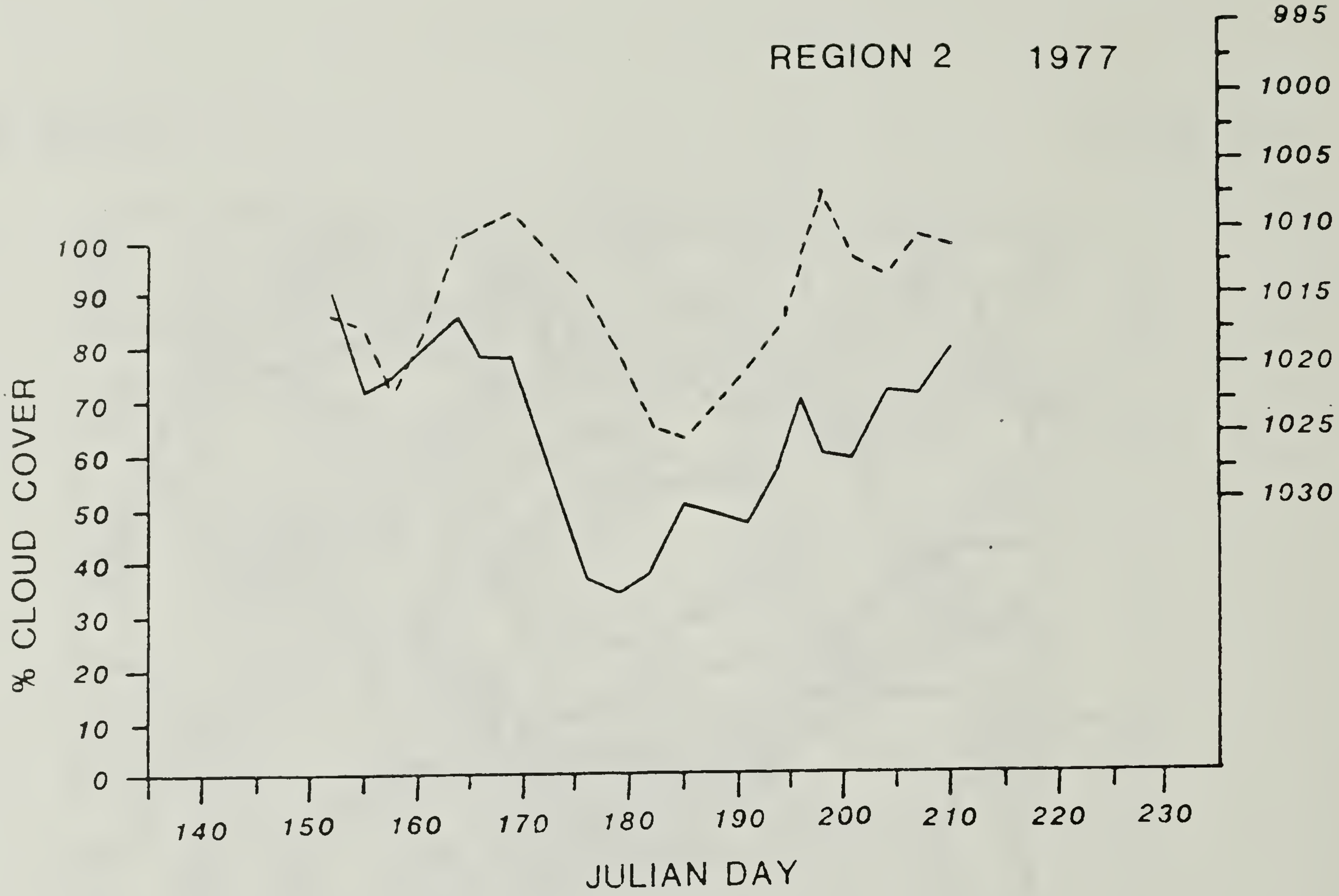


FIGURE 44

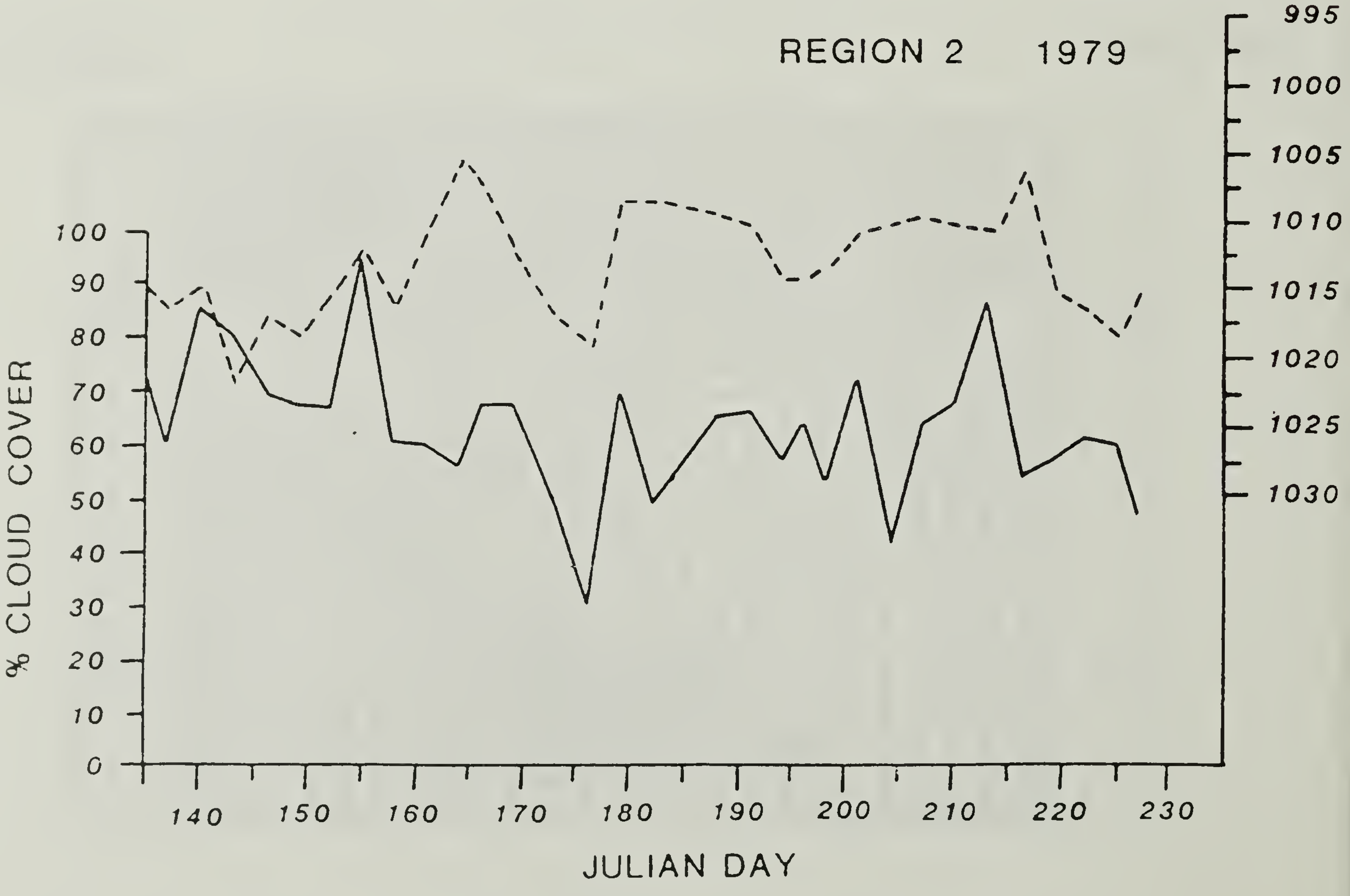
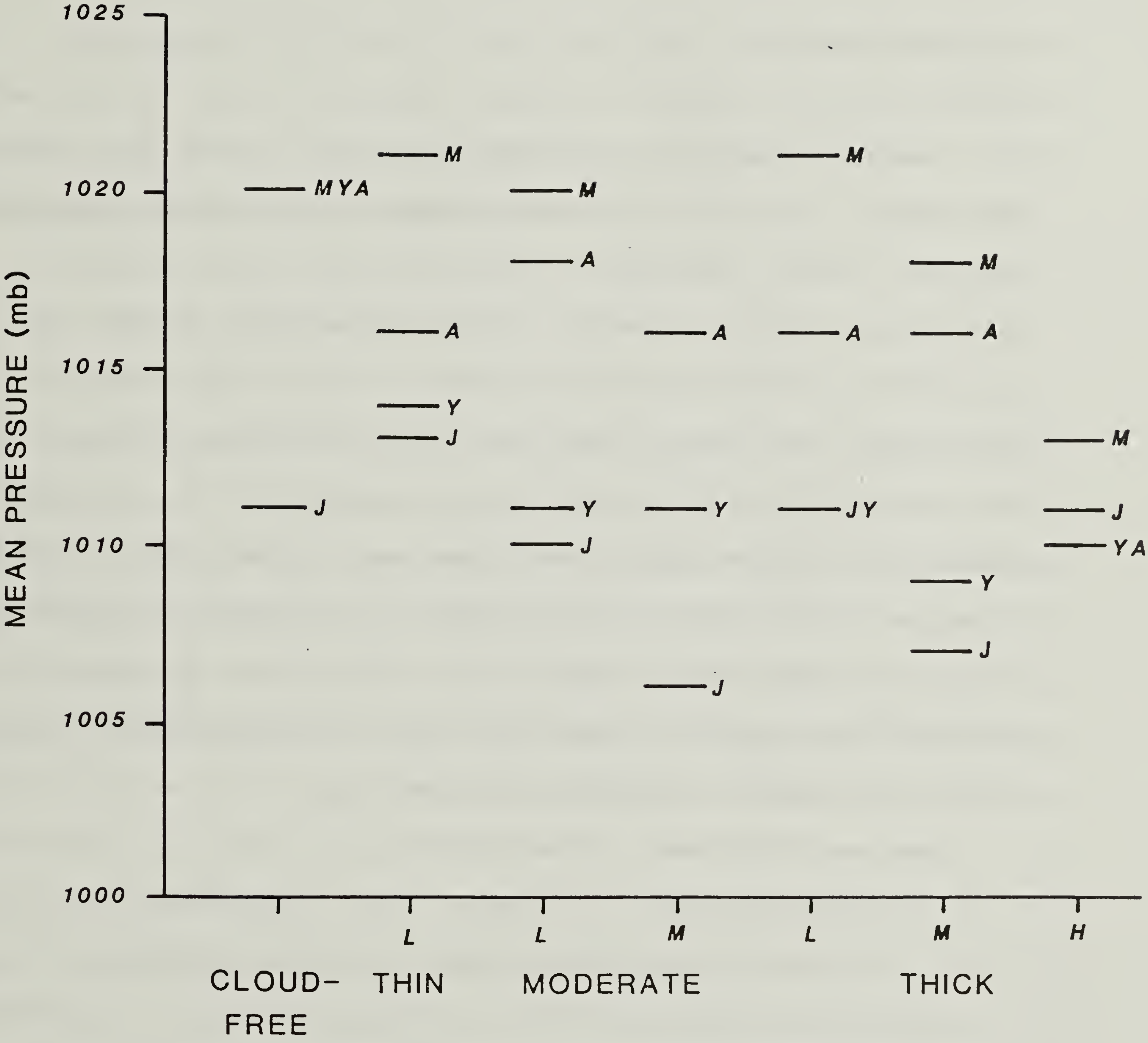


FIGURE 45


1025
1020
1015
1010
1005
1000
MEAN PRESSURE (mb)
MYA
J
M
A
Y
J
M
A
Y
J
A
Y
J
M
A
JY
M
A
Y
J
M
J
YA
L
L
M
L
M
H
CLOUD-FREE
THIN
MODERATE
THICK

APPENDIX 1.

CLOUD CHARTING MANUAL FOR THE ARCTIC BASIN

1. INTRODUCTION

Arctic cloud cover has been studied in the late springs and summers of 1977-1979 using Defense Meteorological Satellite Program (DMSP) imagery as the primary data source. The following guide documents the methodology used in the preparation of the cloud data sets. Clouds were charted using shortwave (SW, .4-1.1 μm) and infrared (IR, 8-13 μm) DMSP imagery in the form of positive transparencies. A complete decription of the DMSP satellites and imagery is provided by Fett and Bohan (1977). Only technical information pertinent to this study will be discussed here. Individual classes of cloud optical thickness and cloud top height were determined visually using the imagery. Classes included:

Optical thickness (cloud cover)

1. cloud-free
2. thin clouds
3. moderately thick clouds
4. thick clouds

Cloud top height

1. high
2. middle
3. low

Data were digitized using the National Meteorological

Center's (NMC) standard Primitive Equation data grid.

2. CHOOSING IMAGES

The overall goal was to achieve daily daylight coverage of the Arctic using a minimum number of images closely related in time. To do so, it was necessary to understand the orbital characteristics of the DMSP satellites.

a. Orbital characteristics:

DMSP satellites have an orbital period of approximately 102 minutes. The orbit is inclined 98.7° with respect to the equator (Figure 1); therefore, the orbiter achieves a maximum latitude of 81.3° N or S. The orbiter scans 13° to either side of nadir, so at 81.3° N or S the imagery extends past the poles. The effect of the 102-minute orbital period is that each pass will be approximately 25.4° west of the preceding one (Figure 2). The orbits are divided into both ascending and descending nodes. The ascending node is defined as the northward leg of the orbit, while the descending node is defined as the corresponding southward leg. Full coverage of the Arctic in as short a time period as possible requires the use of both nodes.

Imagery from an orbiter crossing the equator on the ascending node at local apparent noon (LAN), and from one crossing the equator on the ascending node at dawn were used. With each, the local time at nadir becomes progressively earlier from the equator northward to 81.3°N (ascending node) and then southward to the equator (descending node). Local time also becomes earlier from east to west on an image (Figure 3). For this reason, in the Arctic, the sun will be shining from the right half to the left half on any ascending image oriented with north to the top. The angle will be greater for the dawn rising orbiters (Figure 4).

Image brightness in the shortwave is theoretically corrected with respect to solar angle, however in the summer, due to twilight and low solar angles, SW images become progressivly darker as the descending orbit proceeds southwards. The nature of these lighting changes depends on earth-sun geometry and the type of orbiter. In the Arctic, this problem is not encountered with the dawn-rising orbiters from mid-May to mid-August (Figure 5).

b. Procedure:

A primary pass was first selected to begin constructing a chart. Imagery from this pass had to cover a majority of the basin (ascending and descending nodes), be available in both the SW and IR and the image quality had to be judged acceptable. Another feature considered was the orbit number. An effort was made to minimize the total elapsed time between all images used in the analysis to minimize the effect of moving clouds. Thus, if a number of images were found suitable as a primary image, preference was given to the image that had an orbit number somewhere in the mid-range between the earliest and latest passes with available imagery for that day.

Subsequent images were chosen on the basis of superior quality and proximity in time to the primary pass. While the latter minimized class discontinuities at the charted borders of images, some cloud offset could not be avoided. No attempt was made to 'smooth' or time average these borders, rather, it was assumed that the 'gain' or 'loss' of a class would balance out over an entire region. As the circulation in the Arctic is generally sluggish (cf. text), the problem was seldom severe, rarely exceeding a one class difference.

3. INITIAL MAPPING PROCEDURE

Base maps in polar stereographic projection were drafted on mylar on a scale of $1:15 \times 10^6$. This matches the scale of the DMSP imagery. A DMSP transparency was placed under a base map, and was properly oriented with respect to recognized landmarks. At least three images were needed to provide adequate coverage of the basin. The distributions of cloud thickness and cloud top height within an image were determined visually and color coded on separate base maps.

4. IDENTIFICATION OF CLOUDS AND INTERPRETATION OF THICKNESS

The three classes of cloud optical thickness (thick, moderate and thin) were distinguished from cloud-free regions and from each other on the shortwave DMSP imagery by observing textural differences in image brightness and observing the clarity of land surfaces and transient icepack features. The latter includes leads, melt patterns, multi-year ice floes, polynas or large bodies of open water. The classifications were defined as follows (after Kukla, 1984):

1) Cloud-free: surface features seen with high contrast.

2) Thin clouds: surface features clearly recognizable but with reduced contrast from cloud-free skies.

3) Moderately thick clouds: surface features marginally recognizable through the cloud.

4) Thick clouds (no surface features recognizable)

In situations where multiple cloud decks were present, cloud thickness is the integrated value of all levels. The visual interpretation was assisted by an interactive analysis using a digital image processor. The processor was used primarily to determine cloud thickness categories (cf. Robinson et al., 1983).

Interpretation of imagery was difficult over lead-free sea ice lacking a snow cover. The presence and extent of shadows cast by clouds and, similarly, enhanced brightness on the sunward side of clouds aided the interpretation in this case. Thick clouds cast large well-defined shadows while the shadows cast by thin clouds are poorly defined or invisible (e.g., thin cirrus). In theory, it should be possible to determine the true height of a cloud top above the surface from the geometry of a shadow thrown on a snow-covered surface. This technique has been attempted and seems promising in particular situations with well-defined shadows and a high solar zenith angle. Unfortunately, verification of cloud top height from independent measurements is lacking (Kukla, 1984).

The differentiation of clouds and cloud-free regions also made use of the coincident IR imagery. Middle and high level clouds appeared brighter (colder) than the surface. Low clouds were often difficult to distinguish from cloud-free areas. The relative sharpness of the boundaries between areas with different grey values on IR imagery appeared to be related to thickness. An area of cloud that was clearly defined from the surrounding area by a sharply-defined change in brightness is generally thicker than an area where the change was gradual or indistinct.

In most cases where individual cloud elements were too small to be charted individually, yet comprised more than 90% of a given area, the entire area was assigned the apparent thickness class of the individual elements. This rarely occurred in the Arctic during the charting intervals and when it did it only covered several 100 km^2 at a time.

Another problem in thickness interpretation occurred when a clouded area was over two or more different surfaces and there appeared to be differences in cloud thickness between each. This was most common when part of the cloud overlaid featureless sea ice (white over white enhancing apparent thickness) and part overlaid open water (white over a dark surface, resulting in apparent thinning). Whether differences were real or apparent was determined by observing cloud shadows and cloud edge enhancement and studying IR images.

5. INTERPRETATION OF CLOUD TOP HEIGHT

Interpretation of cloud top height was done visually and relied primarily on the distinction between grey shades on IR images. The colder (in general higher) clouds have lighter grey values. Three classes of height were defined as follows:

1) High level (brightest, cold; usually associated with well defined cyclonic weather systems of several hundred kilometers or greater extent).

2) Middle level (intermediate grey values, cool; generally sharply defined from areas with high level cloud, low clouds and the surface. Usually associated with well defined cyclonic systems)

3) Low level (darkest in the infrared, relatively warm, sometimes warmer than the surface; not previously defined as cloud-free sky. Usually not associated with well defined cyclonic systems)

Classes 1 and 2 were most easily identified. Once they were plotted, class 3 was determined by placing the completed thickness map underneath the height map, and coloring in those areas previously defined as cloud-free. The remaining blank areas on the height map were defined as class 3.

Inversions may lead to a cloud being warmer than lower clouds or cloud-free regions. Thus, if unrecognized, errors in cloud-height charting would result. Fortunately, this situation is rare over the lower elevation basin regions in summer. Only in May and in summer over Greenland was this situation frequently encountered.

The primary limitation to the height analysis is where high clouds are thin yet may be estimated as having middle or low tops using the infrared analysis technique. This is because the temperature of an area with high thin clouds is a function of these clouds as well as warmer clouds, land and/or ocean surfaces lying under them. The lack of recognizeable shadows cast by these clouds prohibits estimates to be made using shortwave imagery. It is uncertain how large an impact this limitation has on our study. However, we believe it to be minimal, as analyses of cloud bands which were identified as having high tops over areas where they were underlain by thick clouds continued to be recognized as high when over regions with no clouds below them. This persisted until they reached dimensions considerably smaller than the grid cells used to digitize the data.

6. DIGITIZING DATA

Data were digitized using the National Meteorological Center's standard Primitive Equation data grid, used previously in a satellite based earth radiation budget atlas (Winston et al., 1979) and an atlas of satellite derived snow cover data (Dewey and Heim, 1981) (Figure 6). A grid cell was categorized according to the predominant cloud thickness or height class within it. Only those cells where greater than 50% of the cell had data were counted.

7. REFERENCES

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Fett, R.W. and Bohan, W.A., 1977: Navy Tactical Applications Guide, Techniques and Applications of Image Analysis. NAVENVPREDRSCHFAT Applications Report 77-03, v. 1.

Kukla, G.J., 1984: Variation of Arctic Cloud Cover During Summer 1979. Lamont-Doherty Geological Observatory Technical Report. LDGO-84-2, 65pp.

Robinson, D., Henderson-Sellers, A., Shine, K.P. and Kukla, G.J., 1983 (abstract): A new method of determining arctic cloud properties from remotely sensed data. International Association for Hydrological Sciences Programme and Abstracts, Hamburg, F.R. Germany, Aug. 1983, 46.

Winston, J.S., Gruber, A., Gray, T.I., Varnadore, M.S., Earnest, C.L. and Mannello, L.P., 1979: Earth-atmosphere Radiation Budget Analyses Derived from NOAA Satellite Data, June 1974-February 1978. Vols. 1 + 2, U.S. Dept. Commerce, NOAA.

8. FIGURE CAPTIONS

Figure 1. Orbital inclination of DMSP satellites. The orbit is inclined 98.7° to the equator; therefore the orbiter achieves a maximum latitude of 81.3° N or S (from Dickinson et al., 1974).

Figure 2. Clockwise progression of DMSP imagery coverage. A-C represent successive orbits. The middle dark line on each is the data subpoint, with the small arrows showing the direction of movement of the orbiter. The outer dark lines indicate the limit of coverage for each image, which is 13° to either side of the data subpoint. Note that there is always coverage of the North Pole.

Figure 3. Variation in local time on an image (ascending node).

Figure 4. Position of the sun with respect to an image with a) a local apparent noon (LAN) rising orbiter and b) a dawn-rising orbiter at June solstice with the orbiter at maximum latitude (81.3° N). With the LAN-rising orbiter, LAN is at approximately 77° W. West of this meridian, over most of the Arctic Basin, the sun is shining from the right half to the left half of the image. With the dawn-rising

orbiter, the sun is shining from the right half to the left half of the entire image and the angle with respect to the image is much greater.

Figure 5. Effect of the terminator on lighting conditions for different orbiters at different times of the year (A-C). The hemisphere in darkness is shaded:

A) Dawn-rising orbiter at June solstice. The entire Arctic is in full daylight.

B) Dawn-rising orbiter at equinox. Most of the Arctic is in darkness.

C) Local apparent noon rising orbiter in early August. On the ascending node, the Arctic is in full daylight. The terminator is approached and passed on the descending node. With this type of orbiter, the terminator is nearly normal to an image oriented with north to the top.

Figure 6. NMC grid used in digitizing cloud charts. Numbers at the corners define the row (sides) and column (top and bottom) designations for the corner grid cells.

FIGURE 1

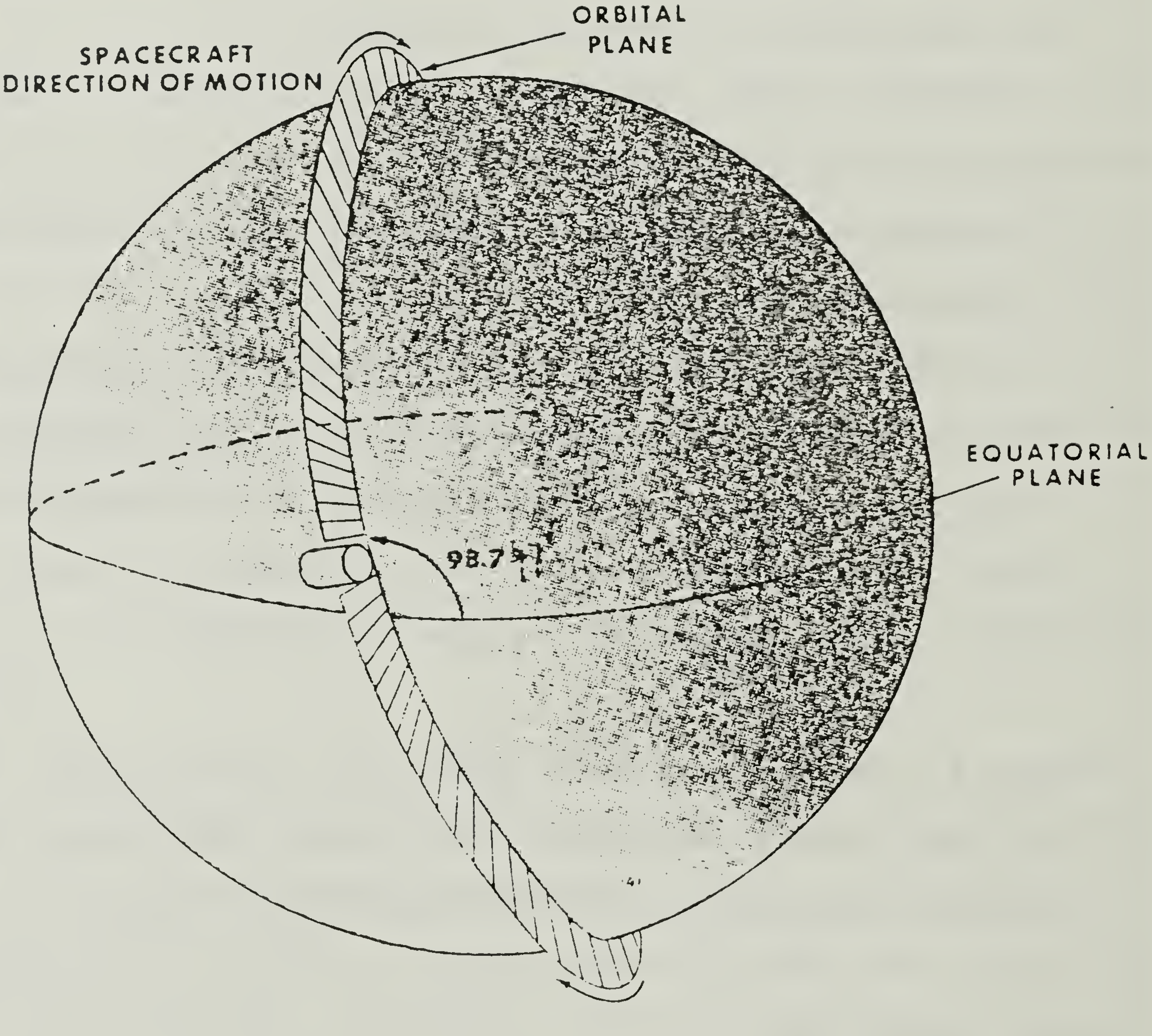

ORBITAL PLANE
SPACECRAFT DIRECTION OF MOTION
EQUATORIAL PLANE
98.7°

FIGURE 2

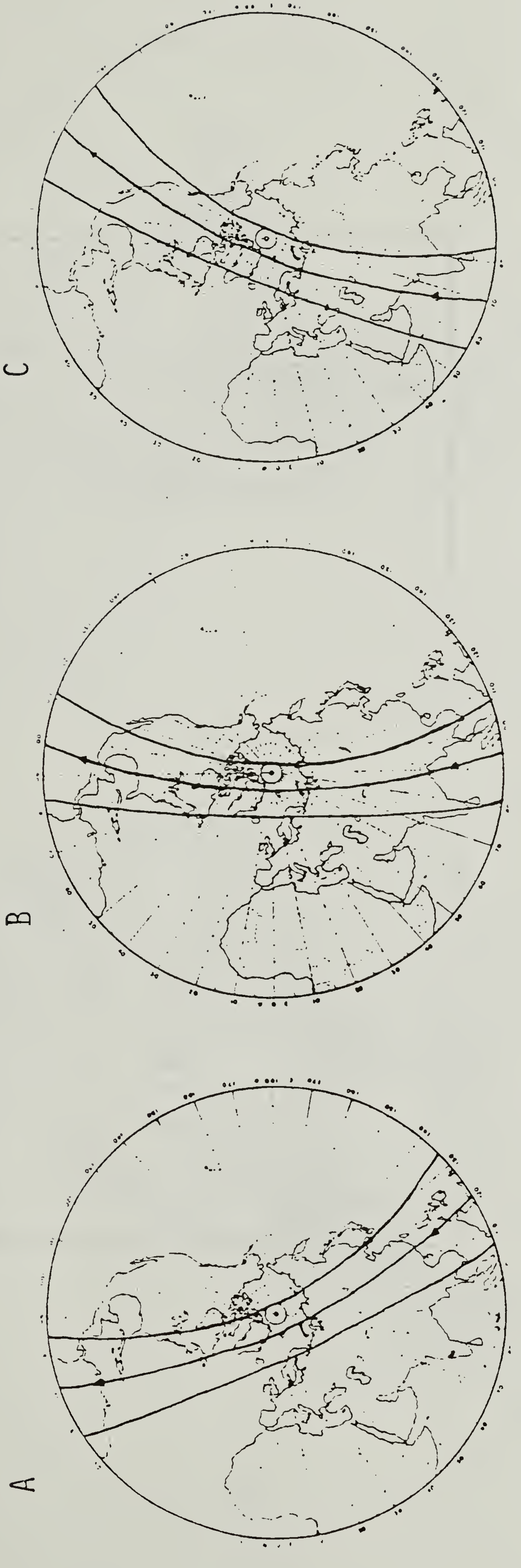


FIGURE 3

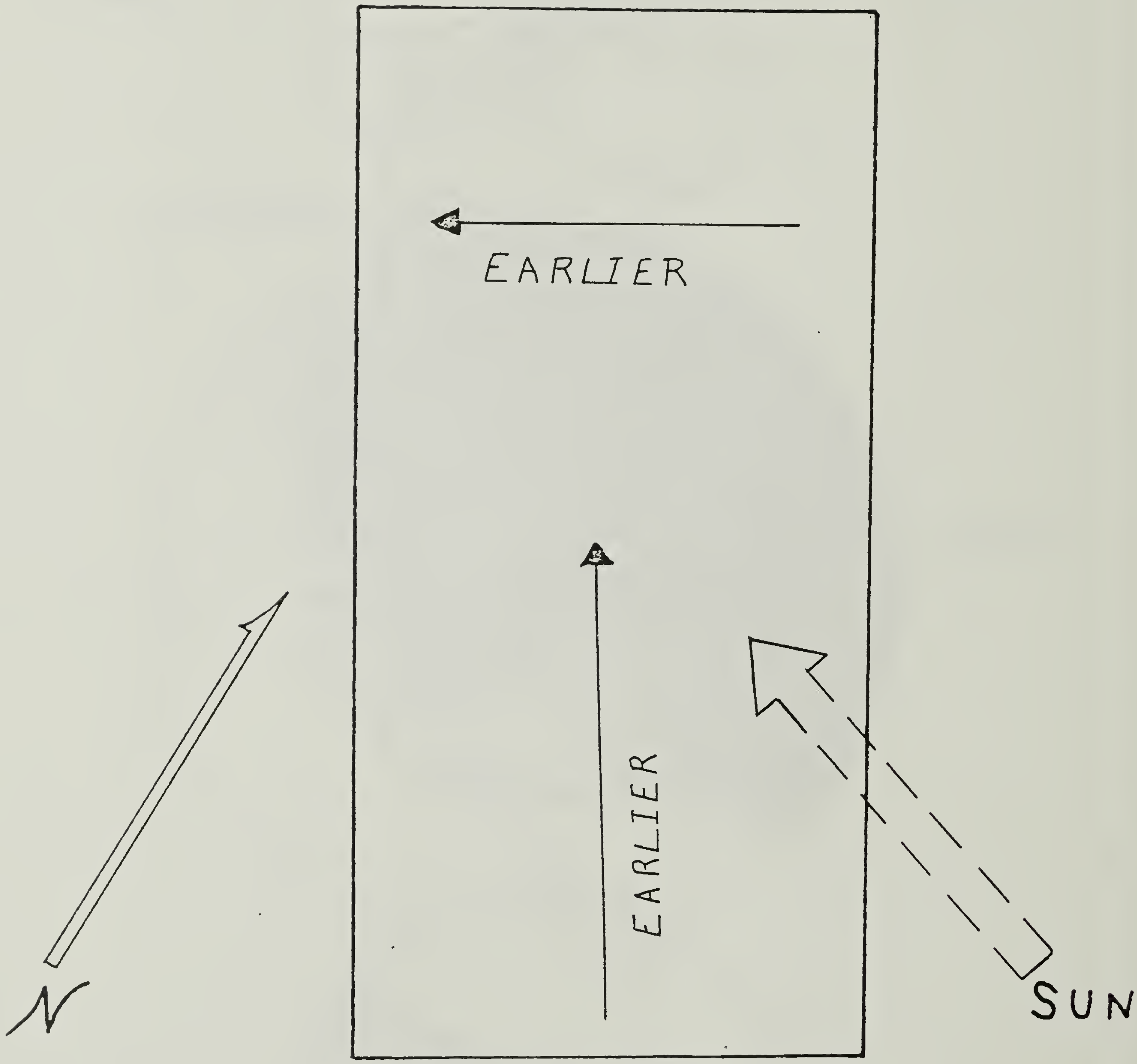
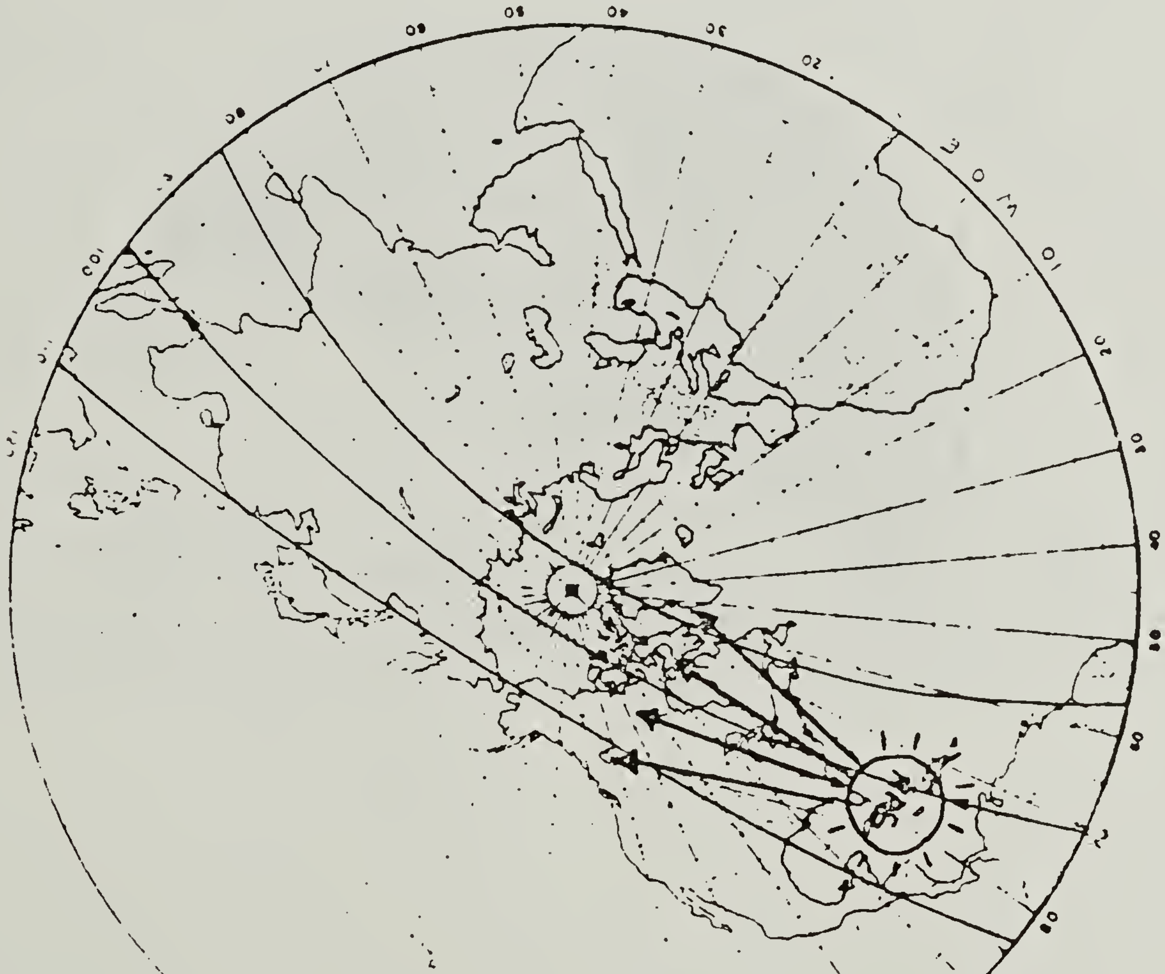


FIGURE 4

A



B

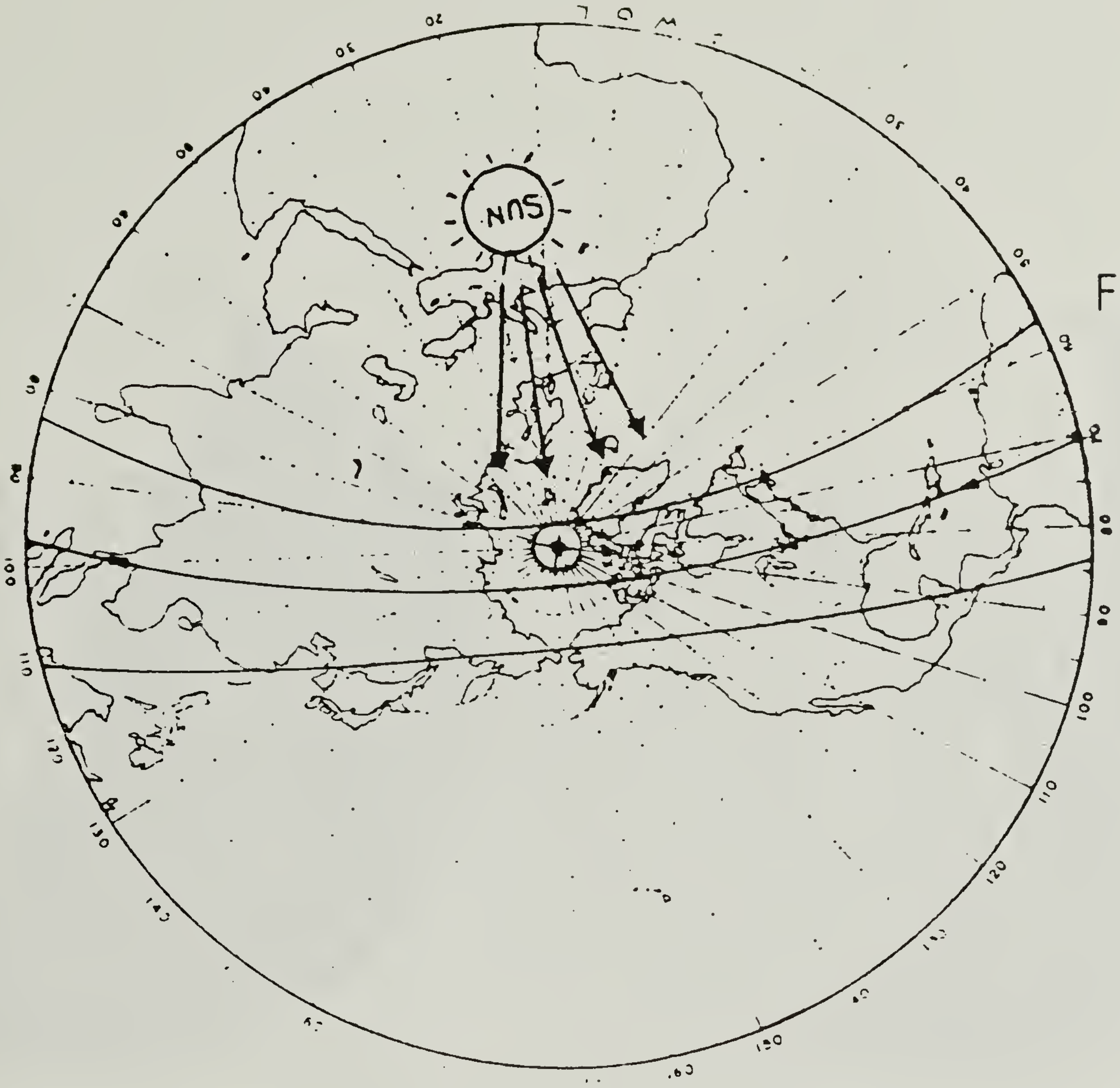


FIGURE 5

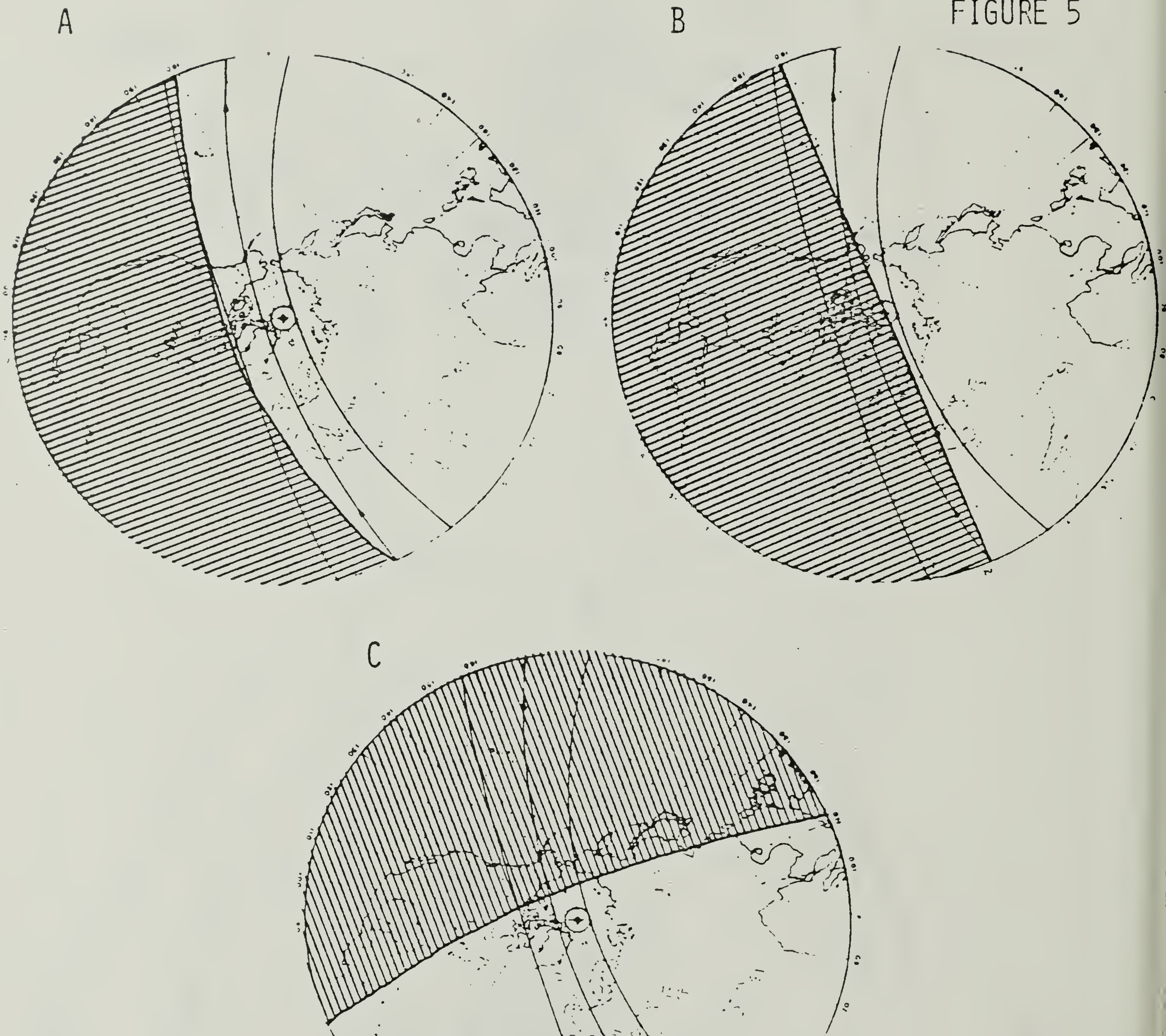
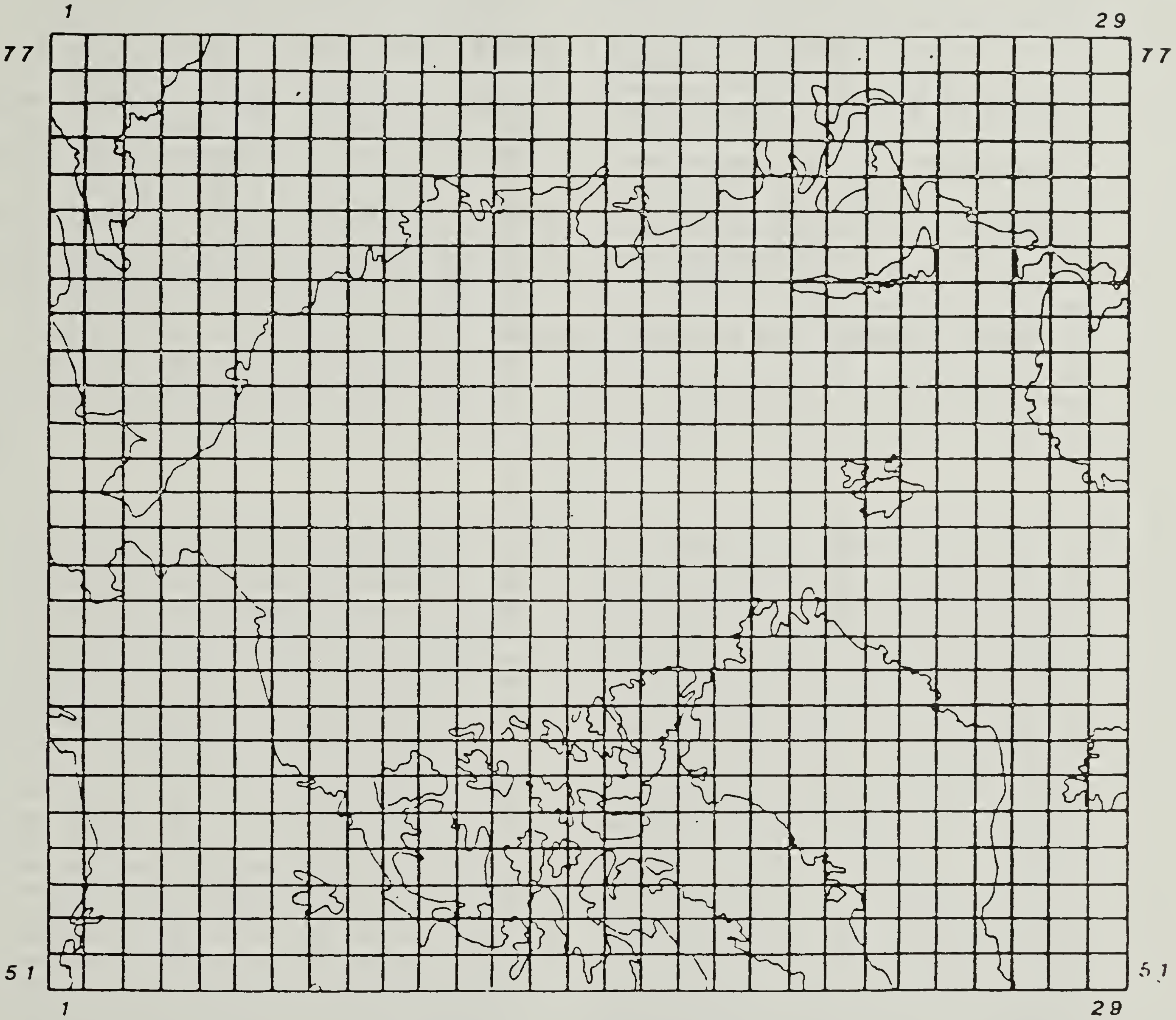


FIGURE 6



APPENDIX 2.

Cloud cover fields generated for the present study in digital format. Numbers on a chart refer to the 4 cloud cover classes: (1: cloud-free, 2: thin clouds, 3: moderately thick clouds, 4: thick clouds). Missing data: 0. The highest and lowest grid row numbers are on the left and the highest and lowest columns are on the bottom.

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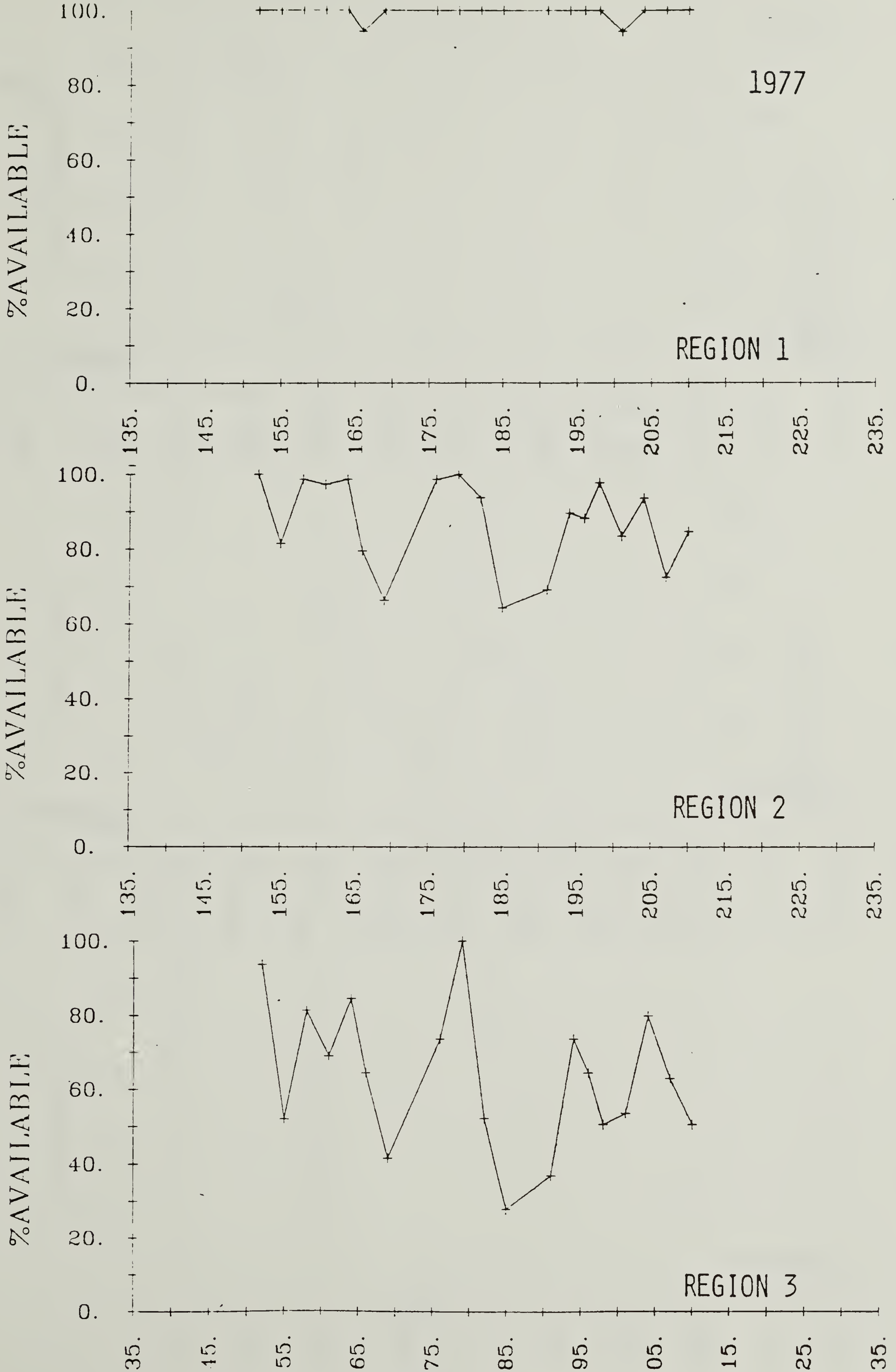
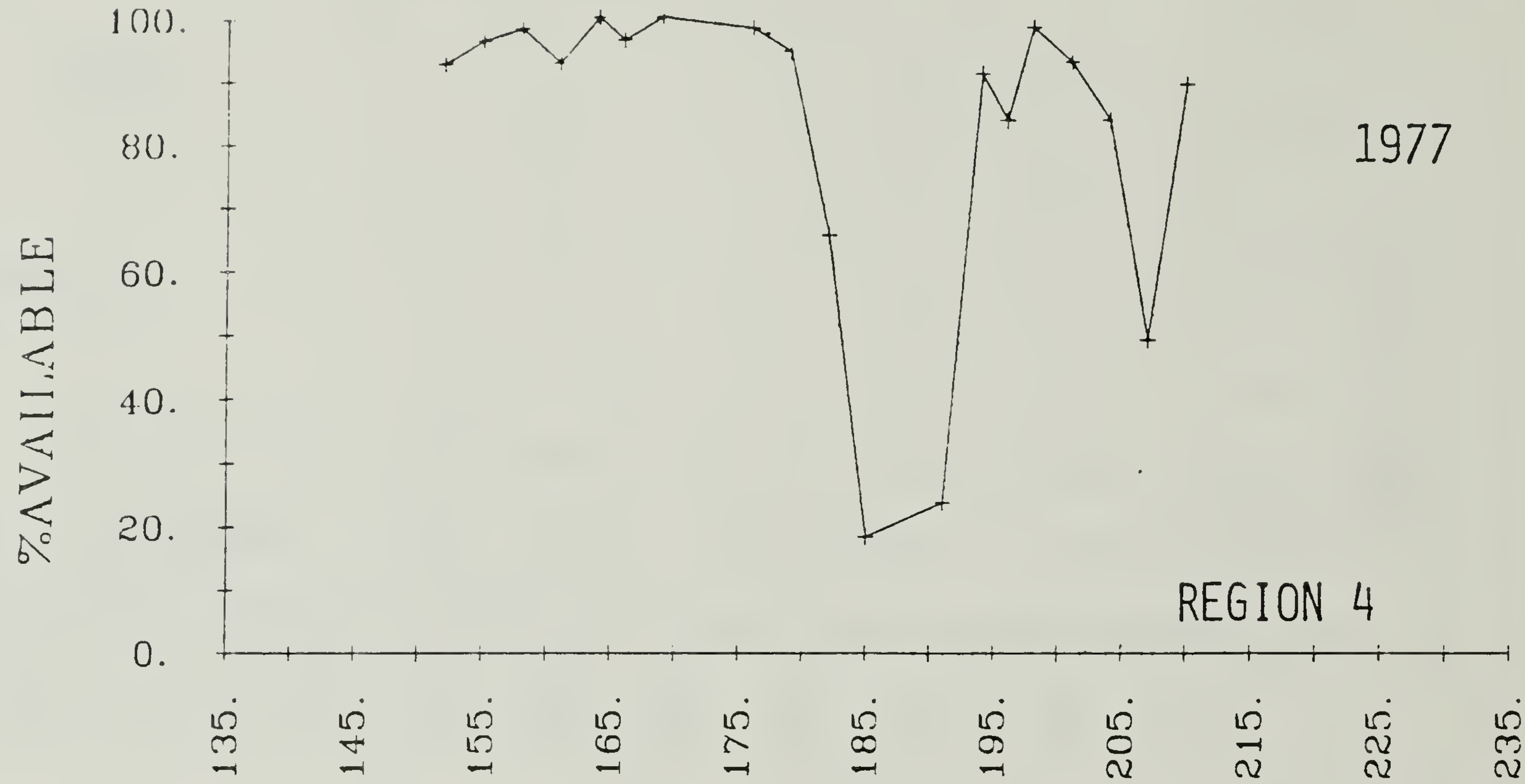
    0 0 0 0 0 0 0 0 0 2 4 3 3 3 3 4 2 2 1 1 1 1 4 4 0 0 0 0 0
    0 0 0 0 0 0 0 0 4 4 4 3 2 2 2 2 2 2 1 3 4 4 4 4 4 4 0 0 0
    0 0 0 0 0 0 4 3 3 4 4 3 3 3 3 2 2 2 1 4 4 4 1 2 4 1 3 3 1
    0 0 0 0 0 4 3 3 3 4 3 3 3 3 2 3 2 1 2 2 1 1 3 1 1 4 1 1 1
    0 0 0 0 0 1 3 3 2 4 3 3 3 3 1 2 2 1 2 1 1 2 4 1 1 1 1 1 0
    0 0 0 0 1 3 3 3 3 3 3 3 3 3 4 2 1 3 3 3 4 2 1 1 1 1 1 3 0
    0 0 0 0 3 3 1 3 3 3 3 3 3 4 4 4 4 3 3 3 3 2 1 1 1 1 3 4 0
    0 0 0 3 3 1 1 3 3 1 1 2 4 4 4 3 4 4 3 1 1 2 2 1 1 2 4 4 0
    0 0 0 3 3 1 3 3 1 2 2 2 3 4 4 3 1 4 3 3 1 4 3 1 2 3 3 3 0
    0 0 3 3 3 1 3 4 4 2 2 1 1 4 4 3 3 1 1 3 3 2 3 3 4 4 4 1 0
    0 0 3 3 3 1 3 4 2 2 2 1 4 4 4 4 2 2 1 4 3 3 3 2 4 2 2 2 0
    0 0 0 0 0 1 3 4 2 2 2 2 3 3 3 1 2 1 1 4 4 4 3 3 4 4 2 2 0
    0 0 0 0 0 1 3 3 2 1 1 2 3 3 1 1 1 1 1 1 3 4 4 3 3 4 3 0 0
    0 0 0 0 0 1 3 3 1 4 1 2 2 2 2 1 1 1 0 0 4 4 4 4 4 3 3 0 0
    0 0 0 0 0 1 3 3 2 4 4 2 2 2 2 2 2 1 0 0 0 4 4 4 4 4 0 0 0
    0 0 0 0 0 3 3 1 1 2 2 2 2 2 1 2 2 0 0 0 0 0 4 4 4 0 0 0 0
    0 0 0 0 0 0 4 3 1 1 2 2 2 2 2 2 2 1 0 0 0 0 0 0 0 0 0 0 0
    0 0 0 0 0 0 0 4 1 1 1 1 2 2 1 2 2 1 1 1 0 0 0 0 0 0 0 0 0
    0 0 0 0 0 0 0 0 1 1 1 1 1 1 4 3 1 1 1 1 1 0 0 0 0 0 0 0 0
    0 0 0 0 0 0 0 0 1 1 1 1 1 3 3 3 3 3 1 1 1 0 0 0 0 0 0 0 0
    0 0 0 0 0 0 0 0 0 0 1 2 1 1 4 4 0 0 0 0 0 0 0 0 0 0 0 0 0
51  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

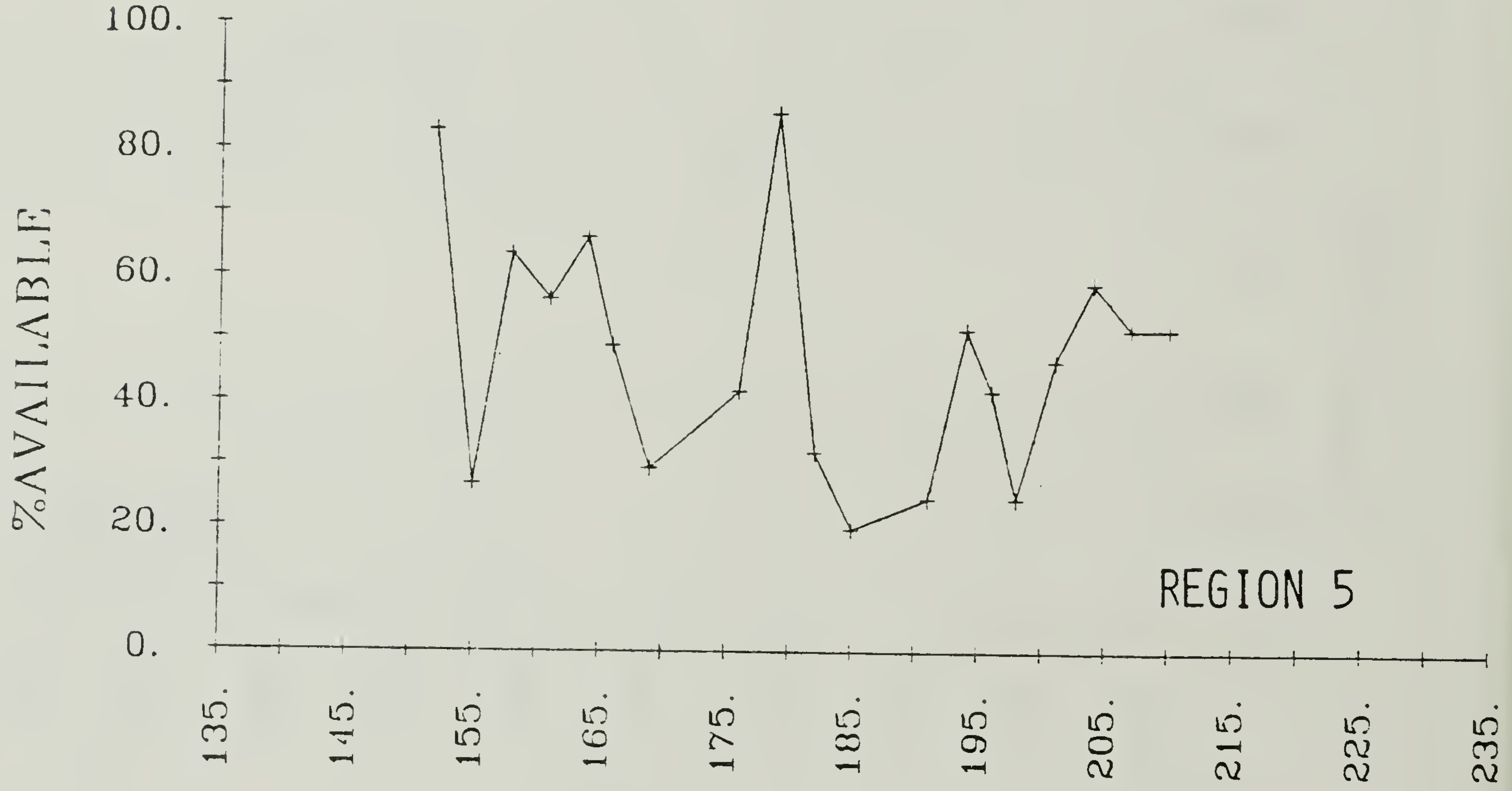
    1                                                       29
```

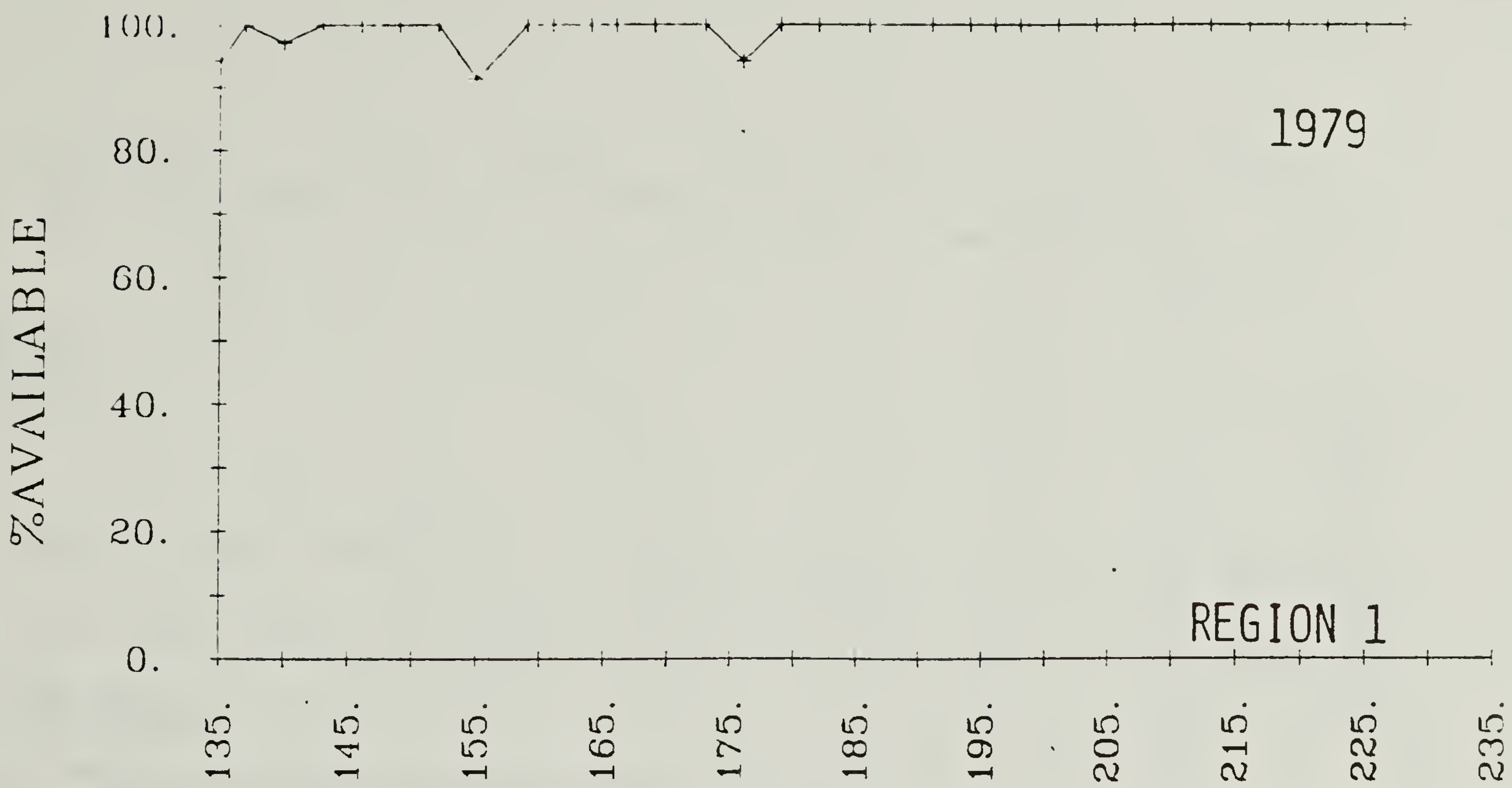
APPENDIX 3.

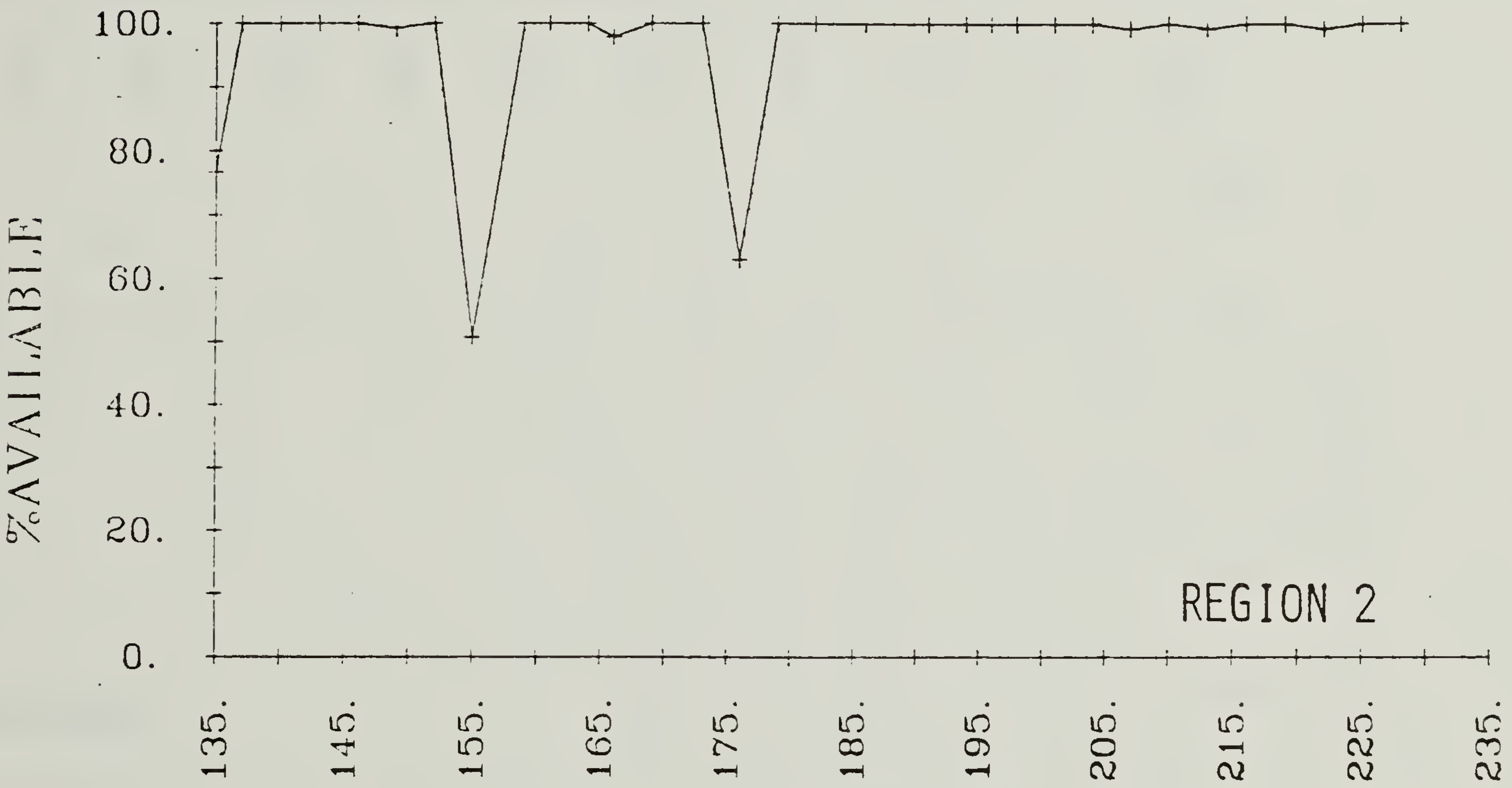
Percentage of grid cells within a region with cloud cover data. For all chart dates from June 1 (Julian Day 152 (horizontal scale)) to July 29 (JD 210), 1977 and May 15 (JD 135) to August 15 (JD 227), 1979.

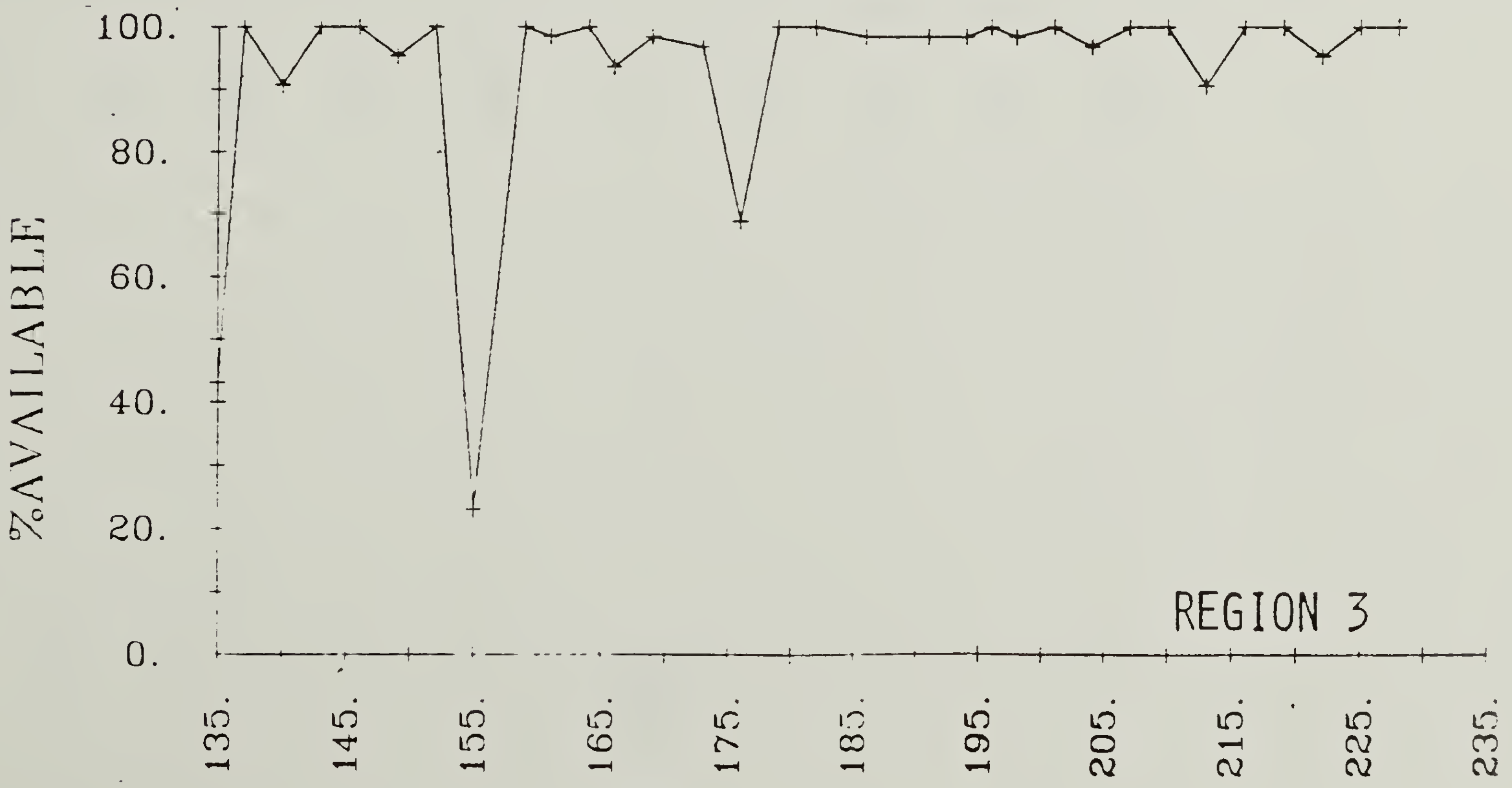

1977
%AVAILABLE
100.
80.
60.
40.
20.
0.
REGION 1
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.
%AVAILABLE
100.
80.
60.
40.
20.
0.
REGION 2
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.
%AVAILABLE
100.
80.
60.
40.
20.
0.
REGION 3
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

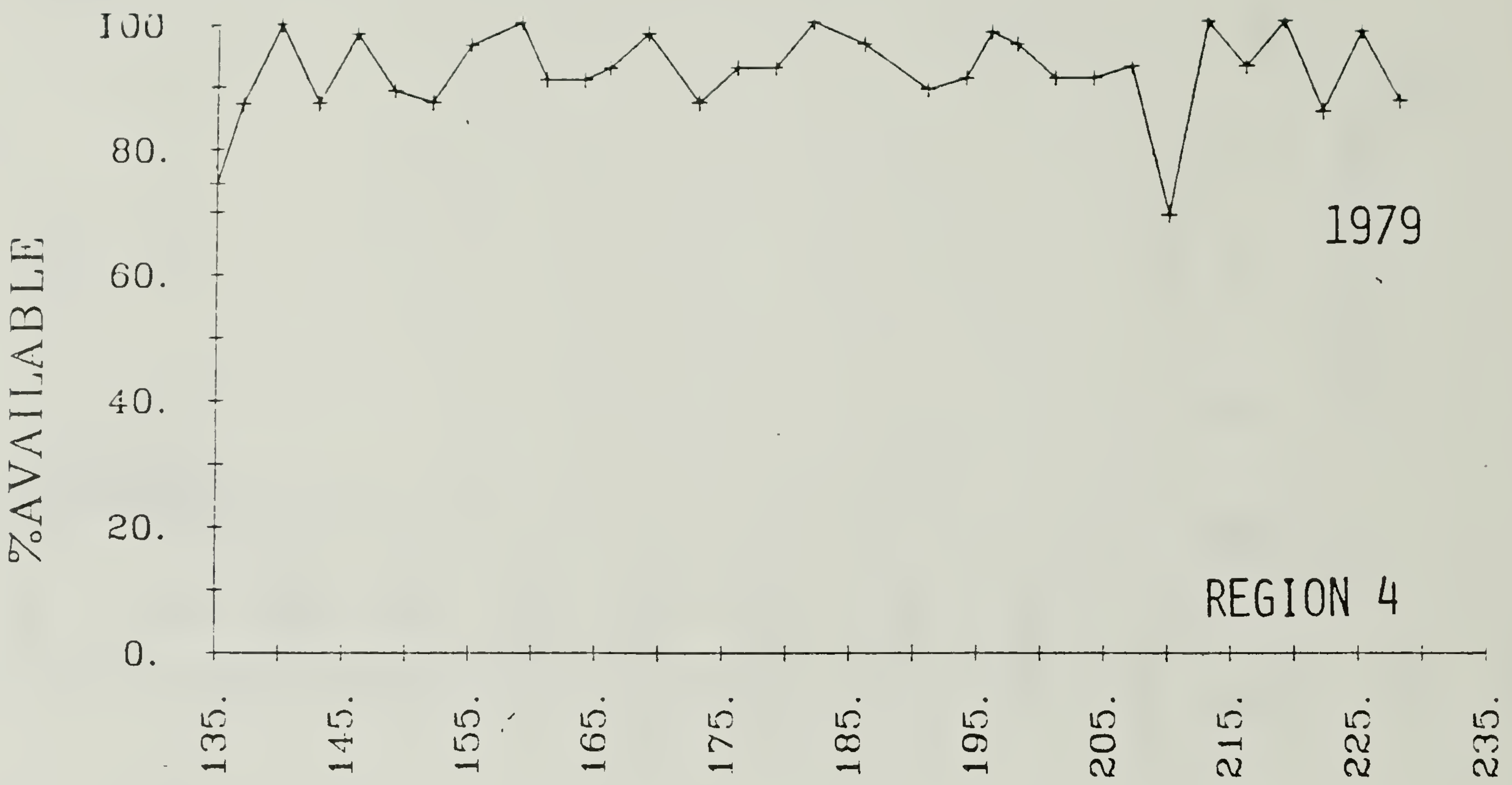

1977
REGION 4
%AVAILABLE
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

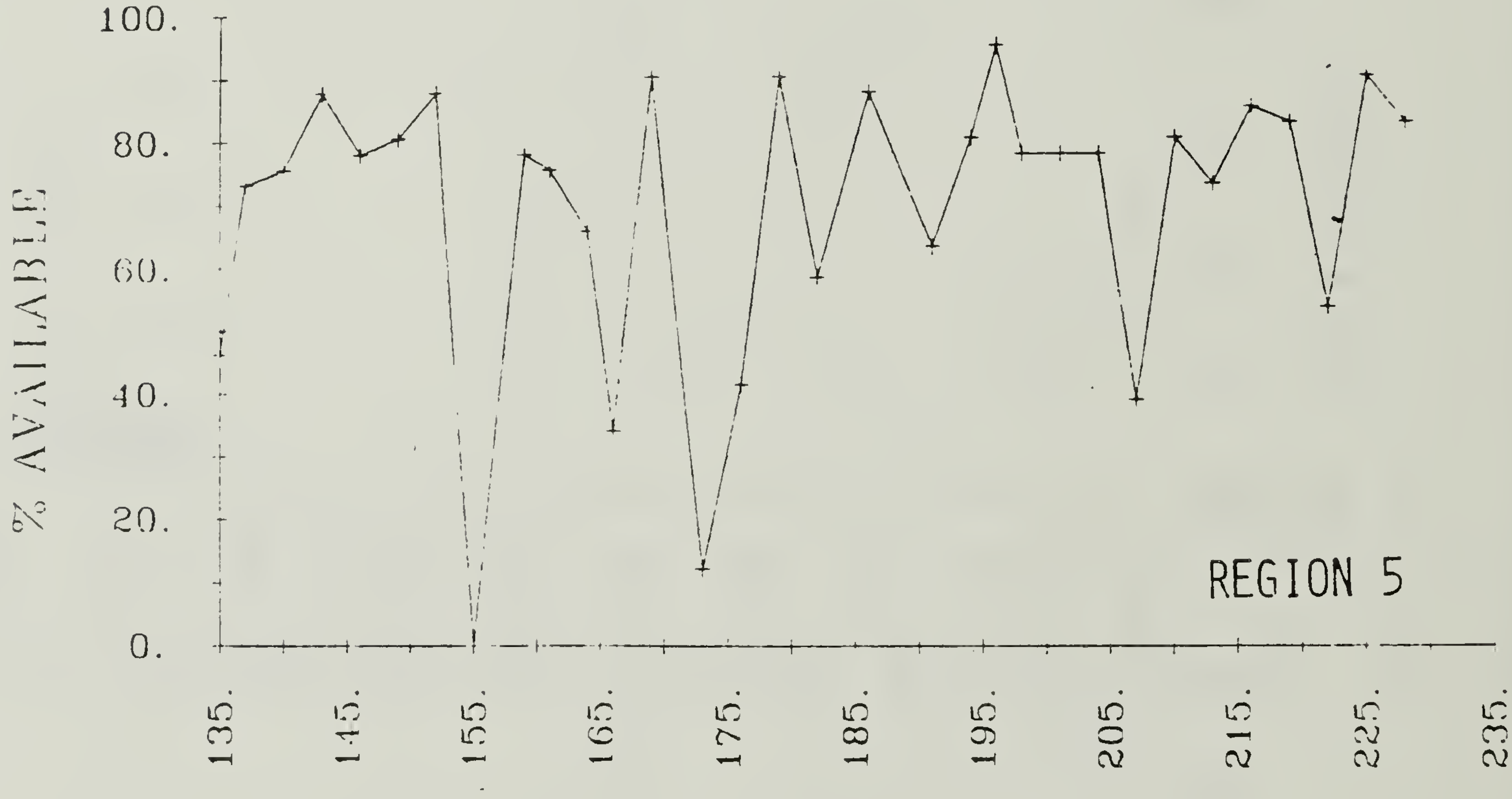

REGION 5
%AVAILABLE
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.


1979
REGION 1
%AVAILABLE
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.


REGION 2
%AVAILABLE
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

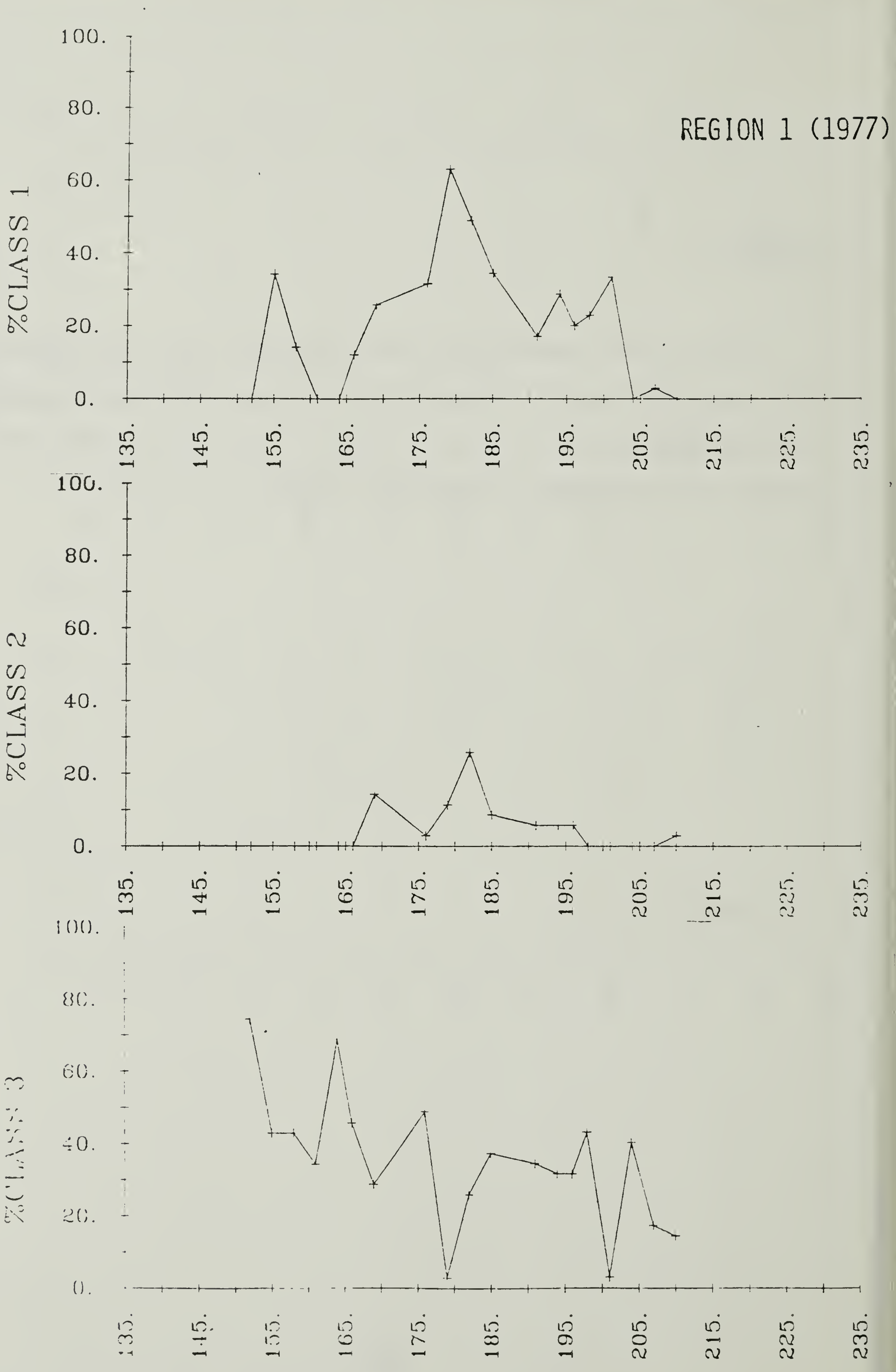

REGION 3
%AVAILABLE
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

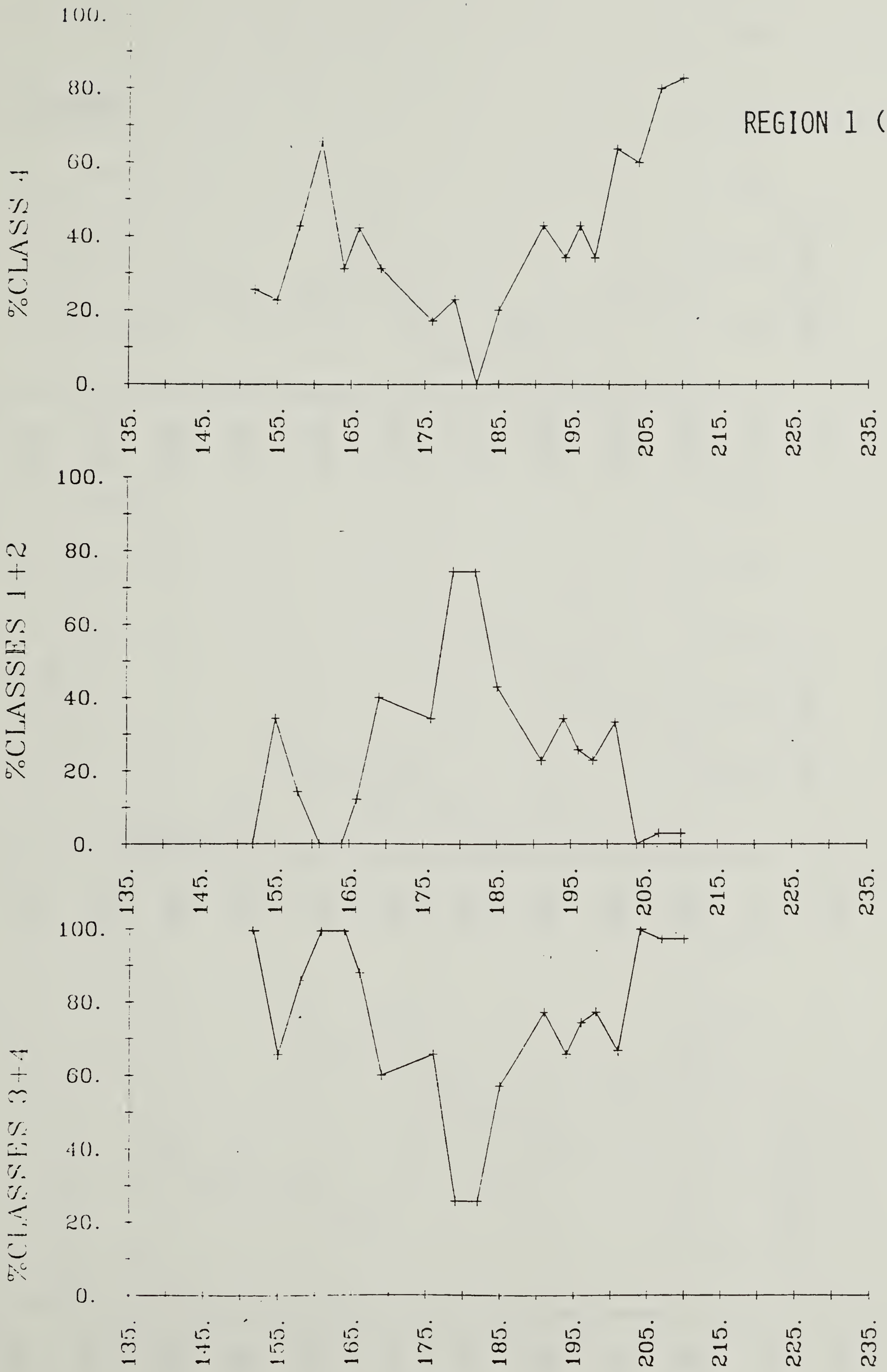

%AVAILABLE
100
80.
60.
40.
20.
0.
1979
REGION 4
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.


% AVAILABLE
100.
80.
60.
40.
20.
0.
REGION 5
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

APPENDIX 4.

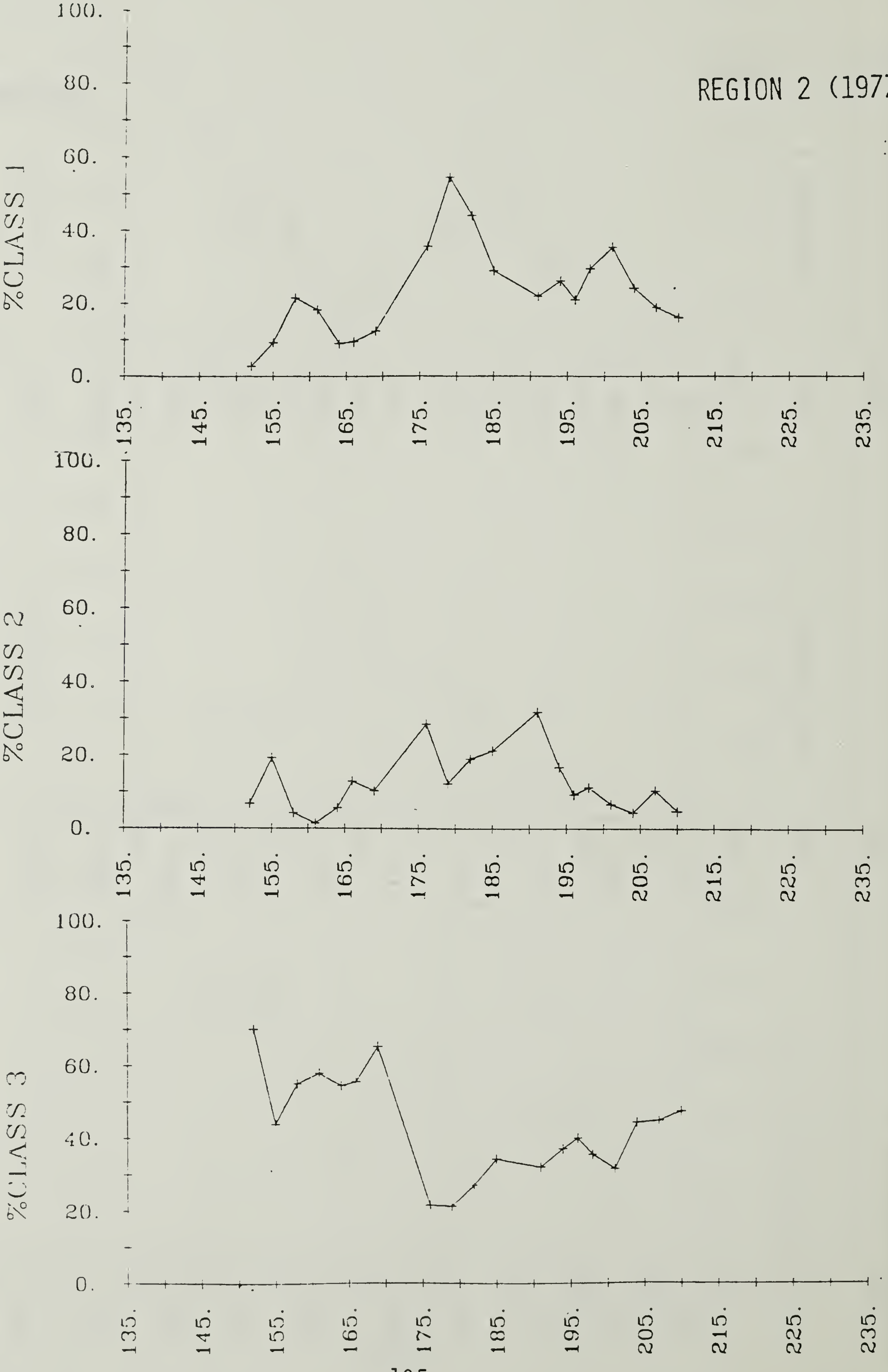
Daily cloud amounts by cloud class(es) for each region in 1977 and 1979 derived from charts running from June 1 (Julian Day 152 (horizontal scale)) to July 29 (JD 210), 1977 and May 15 (JD 135) to August 15 (JD 227), 1979.

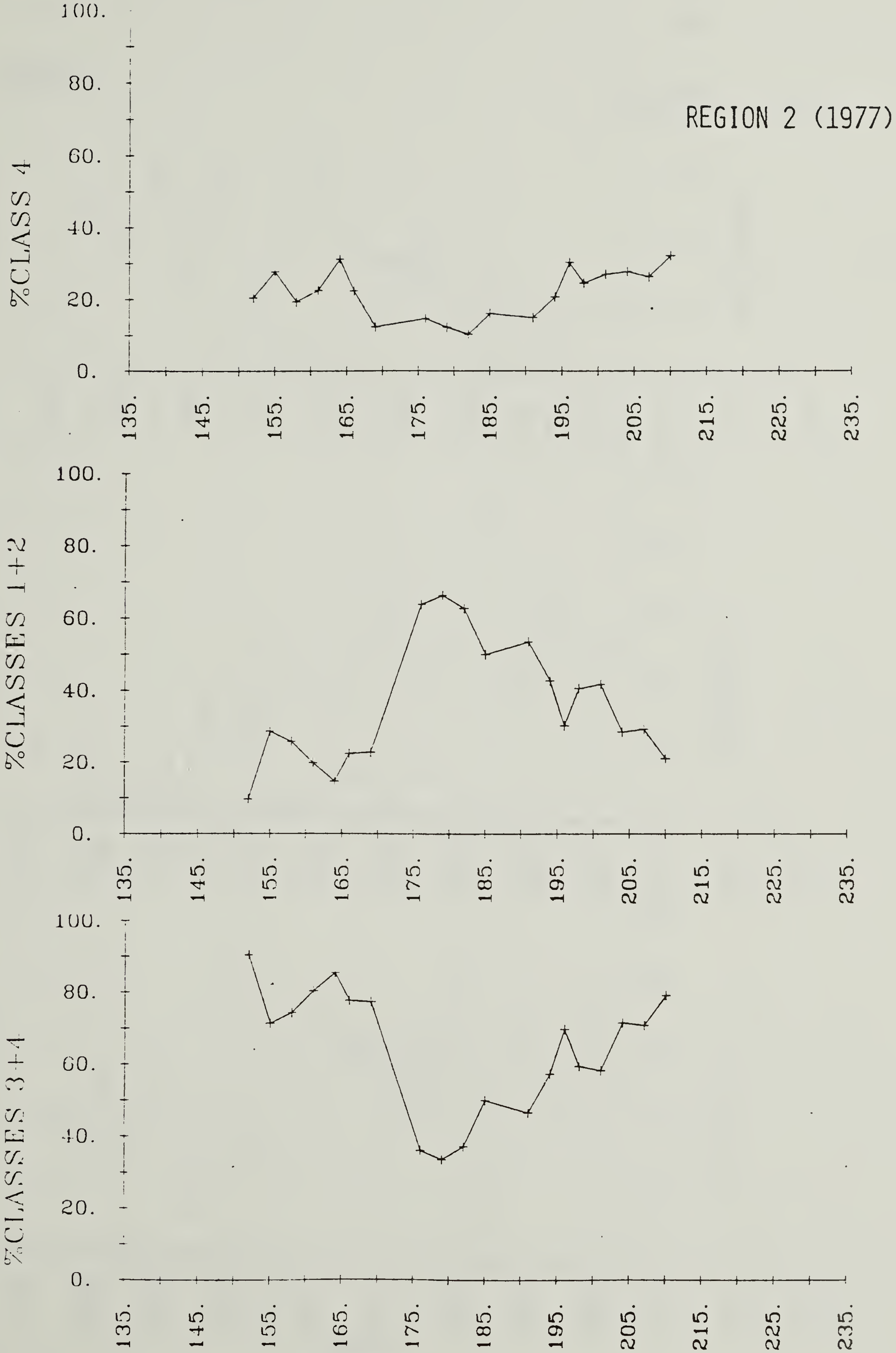
REGION 1 (1977)
%CLASS 1
%CLASS 2
%CLASS 3
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

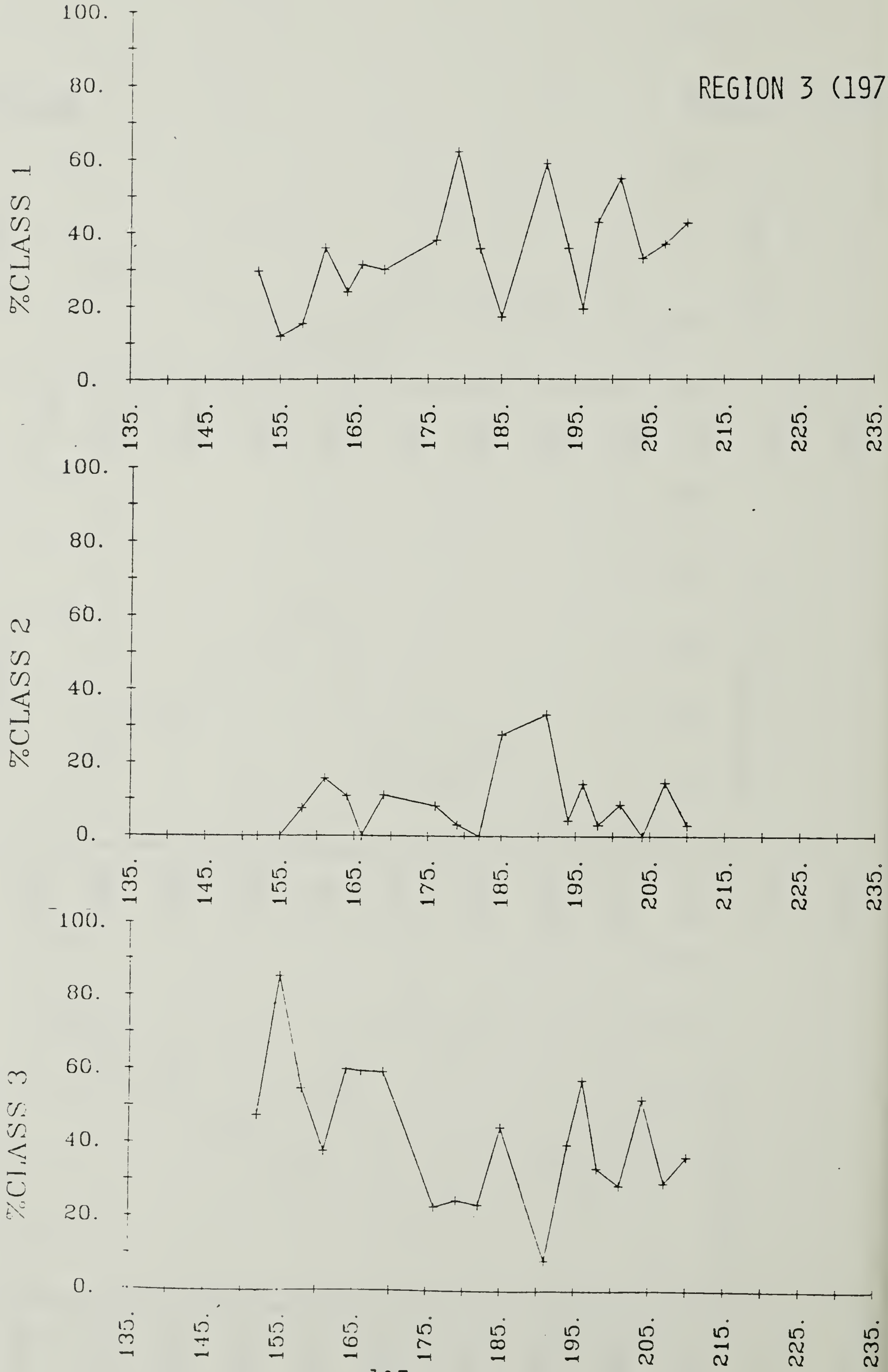


REGION 1 (1977)

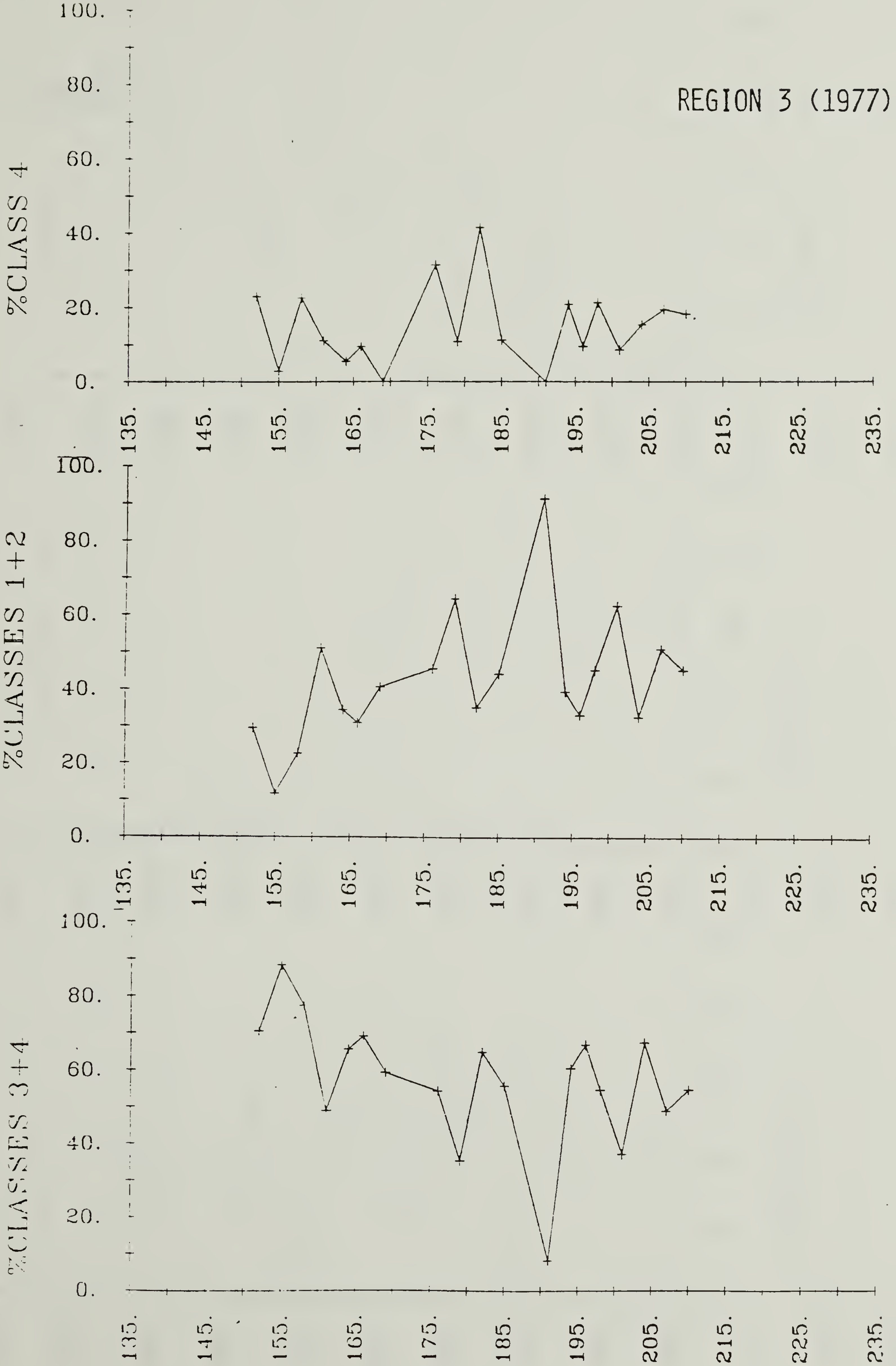
REGION 2 (1977)

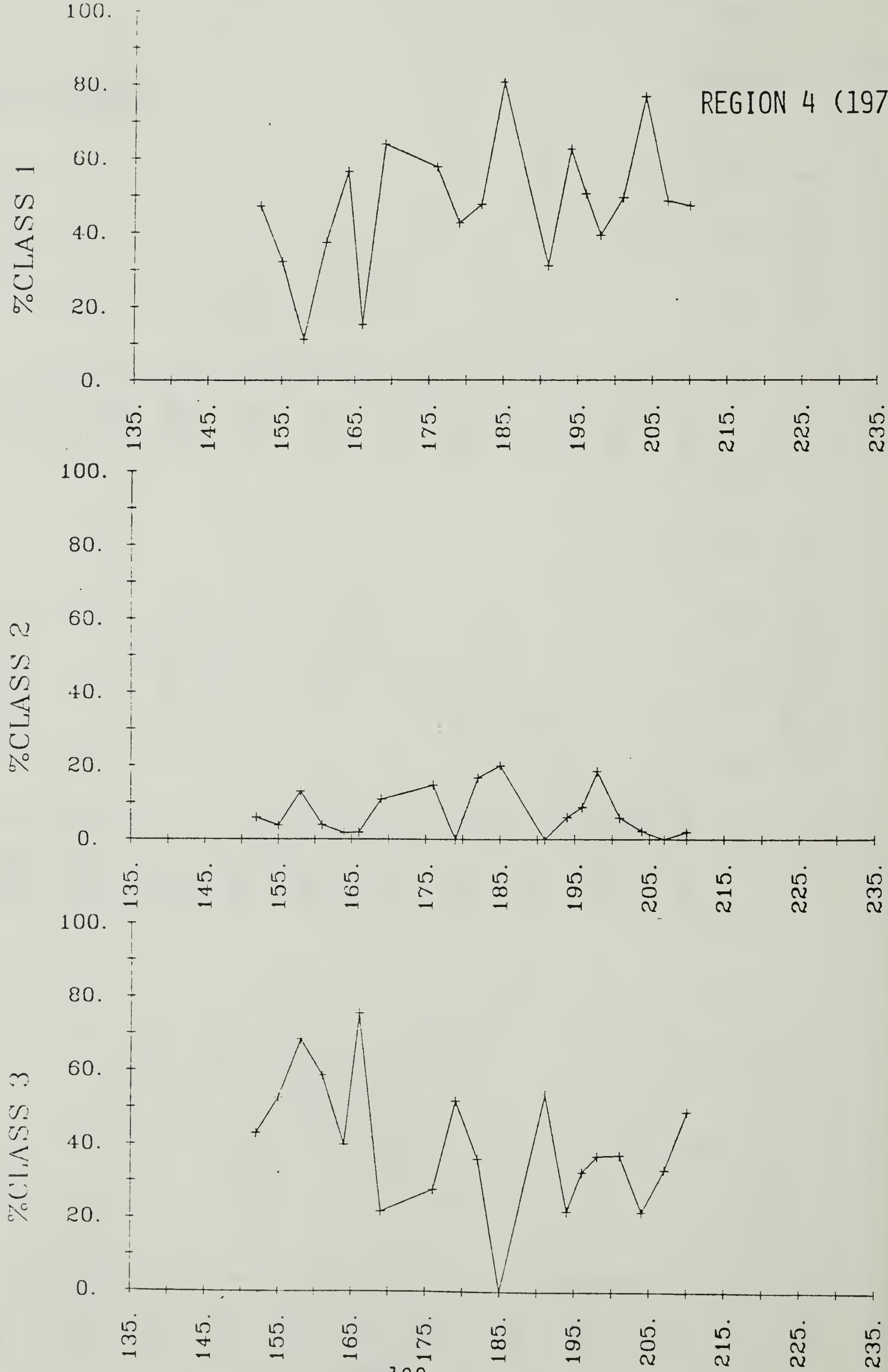



REGION 2 (1977)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

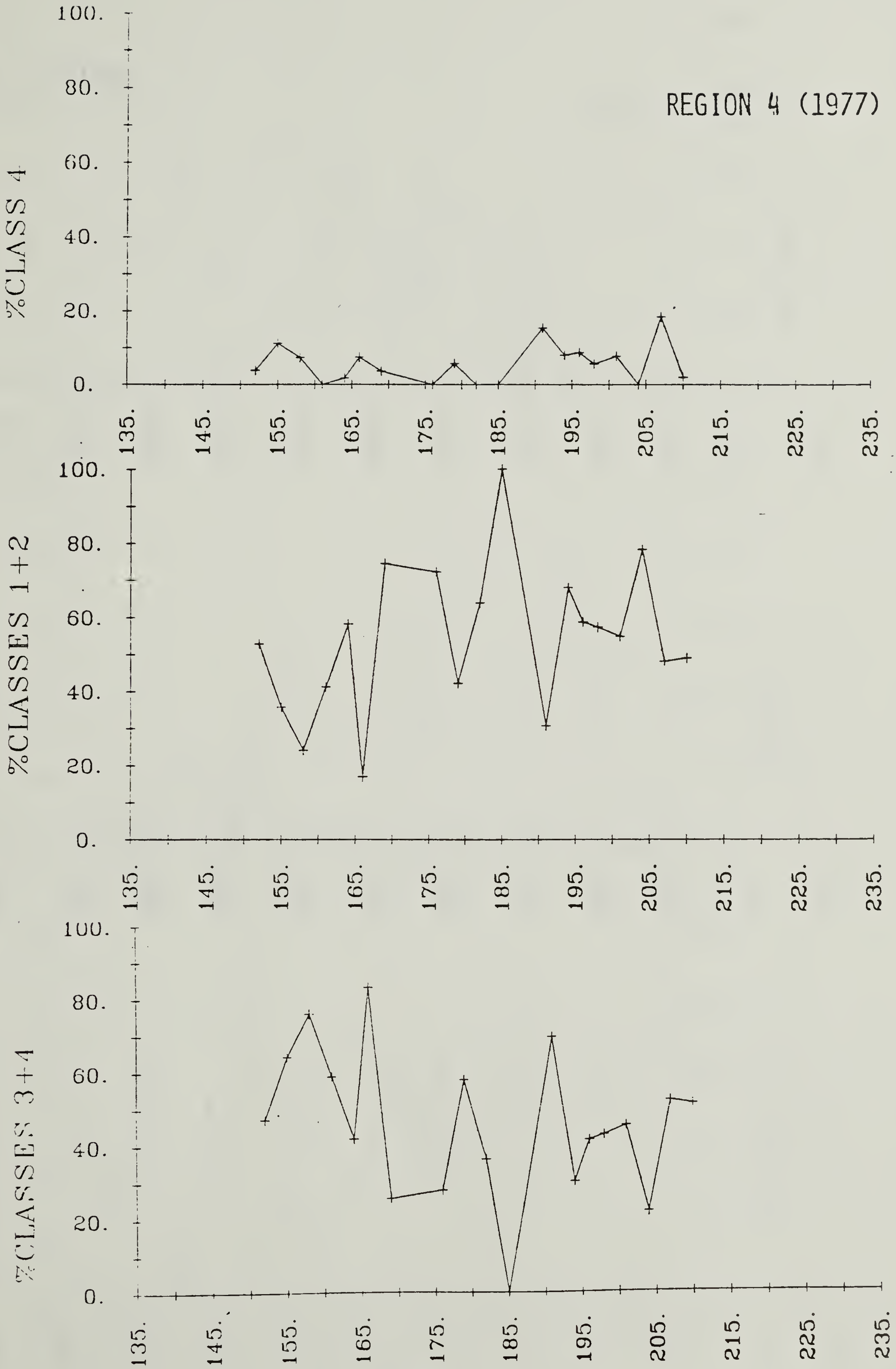


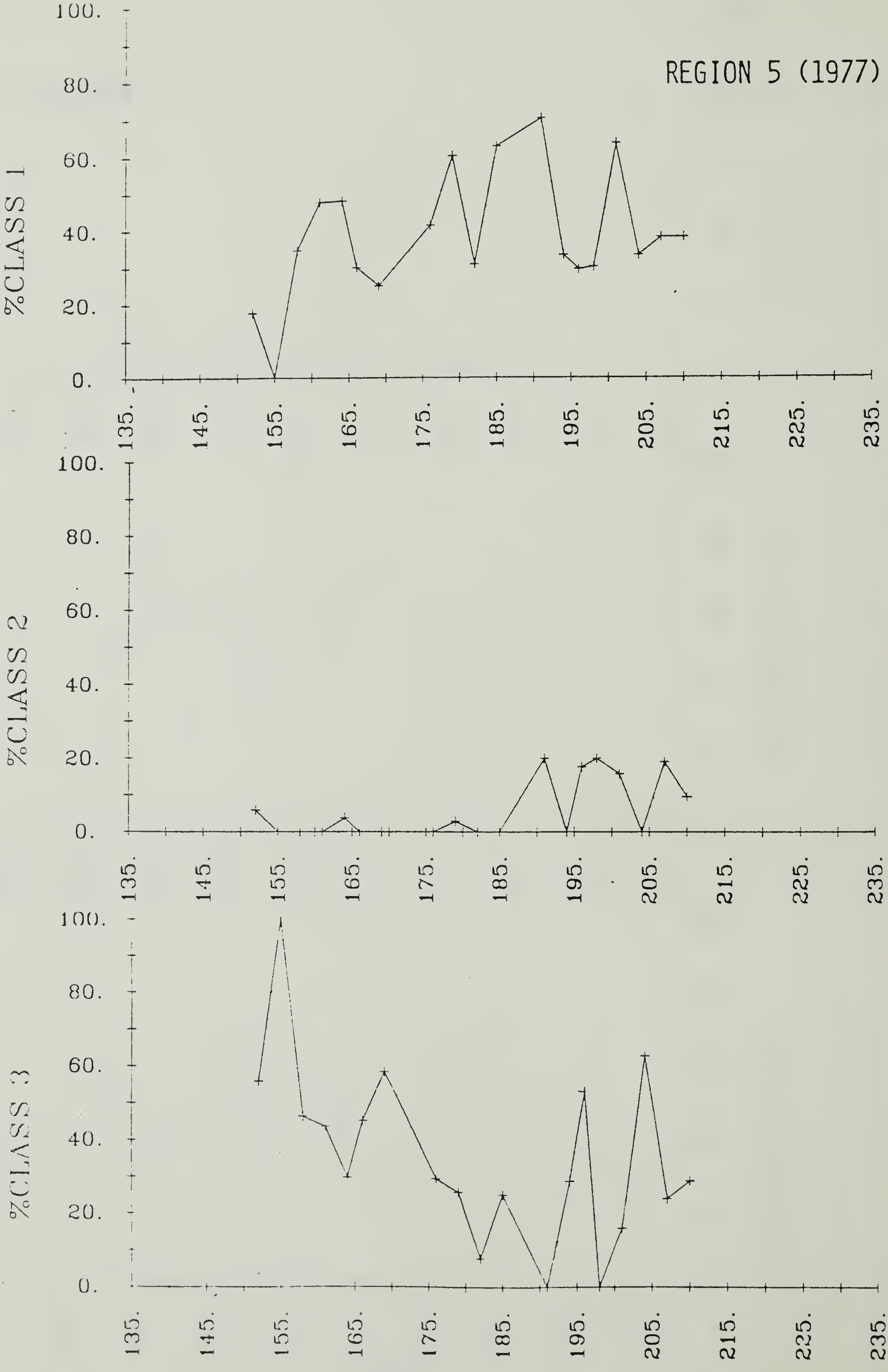
REGION 3 (1977)

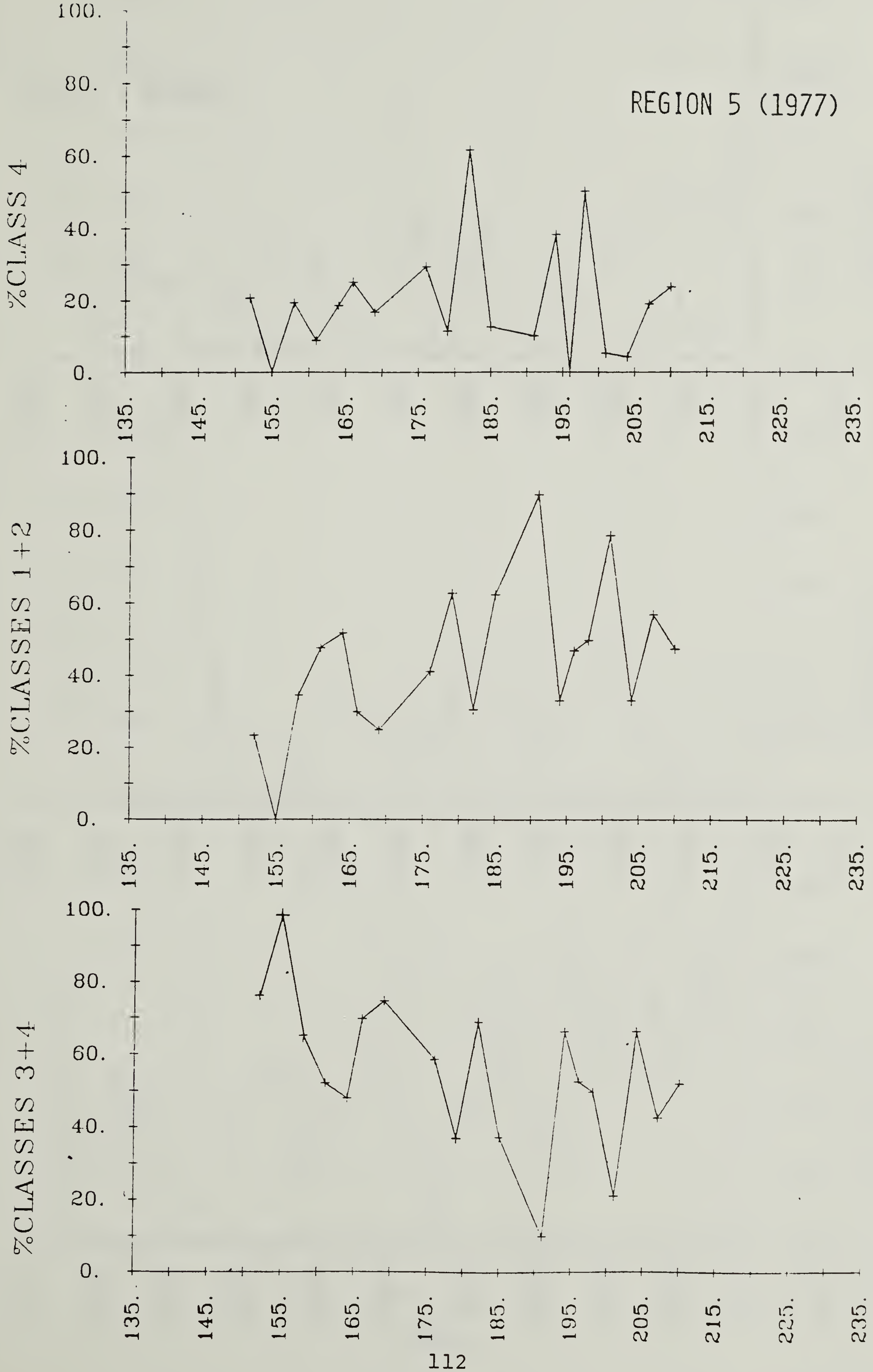

REGION 3 (1977)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

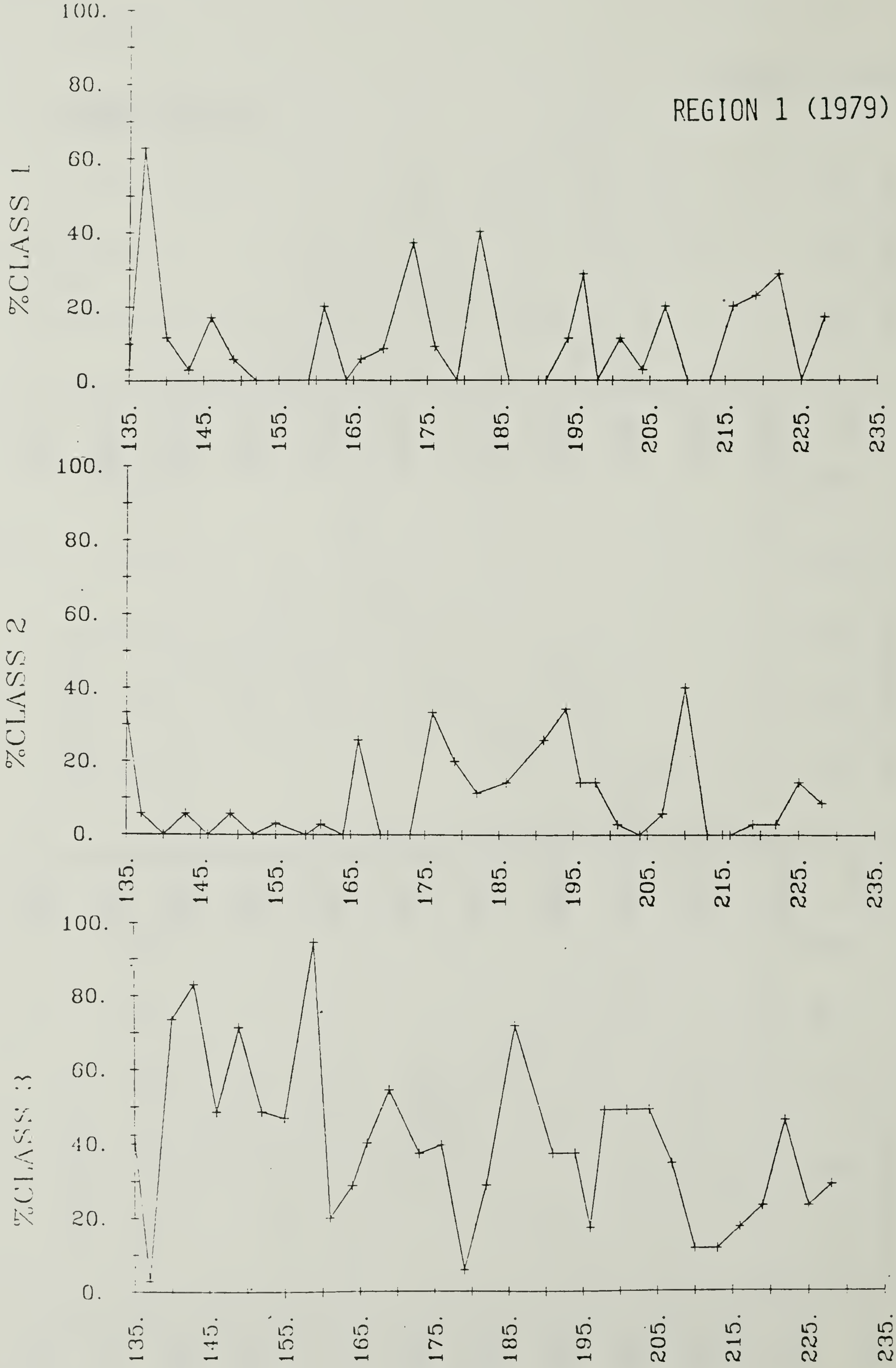


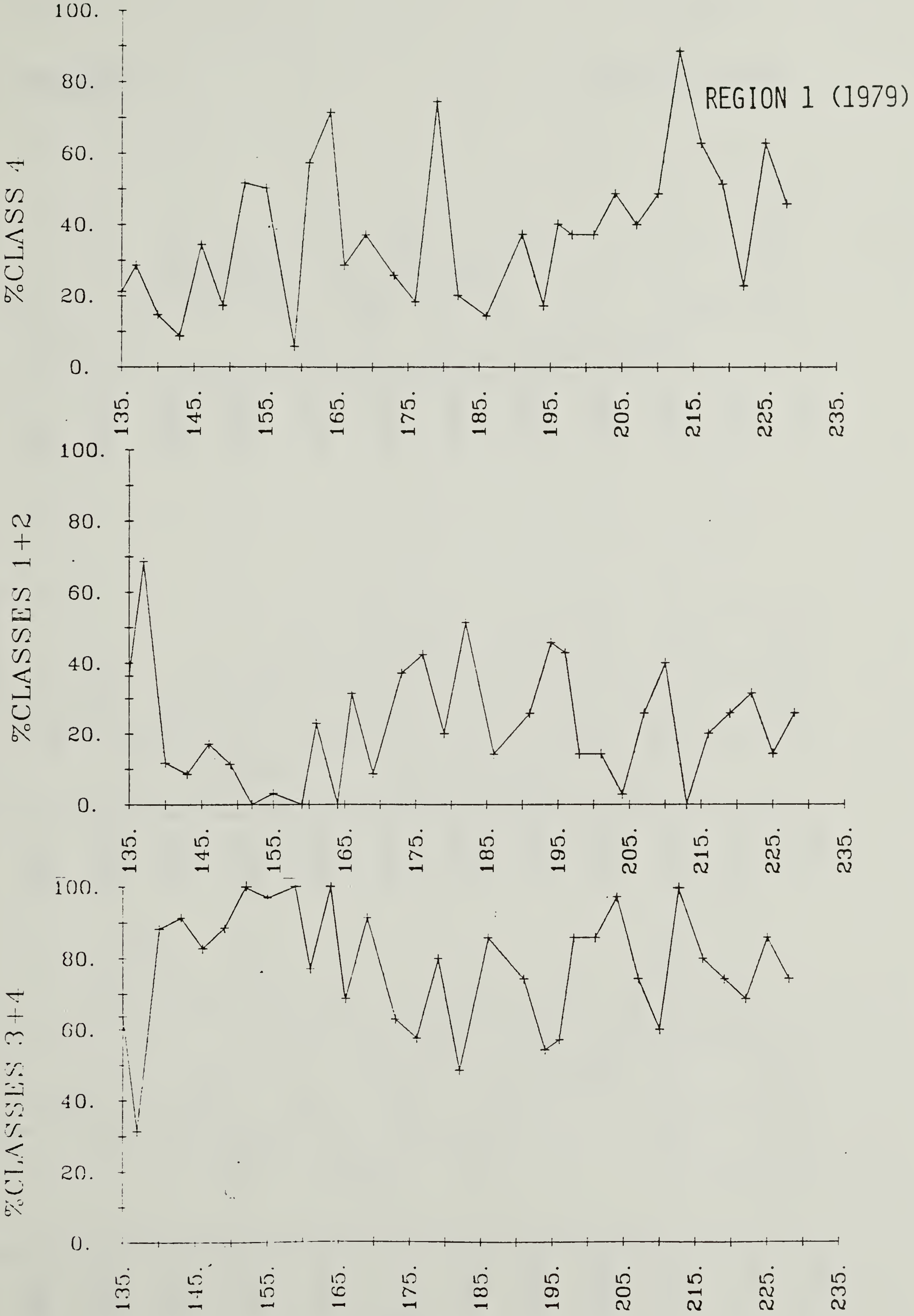
REGION 4 (1977)

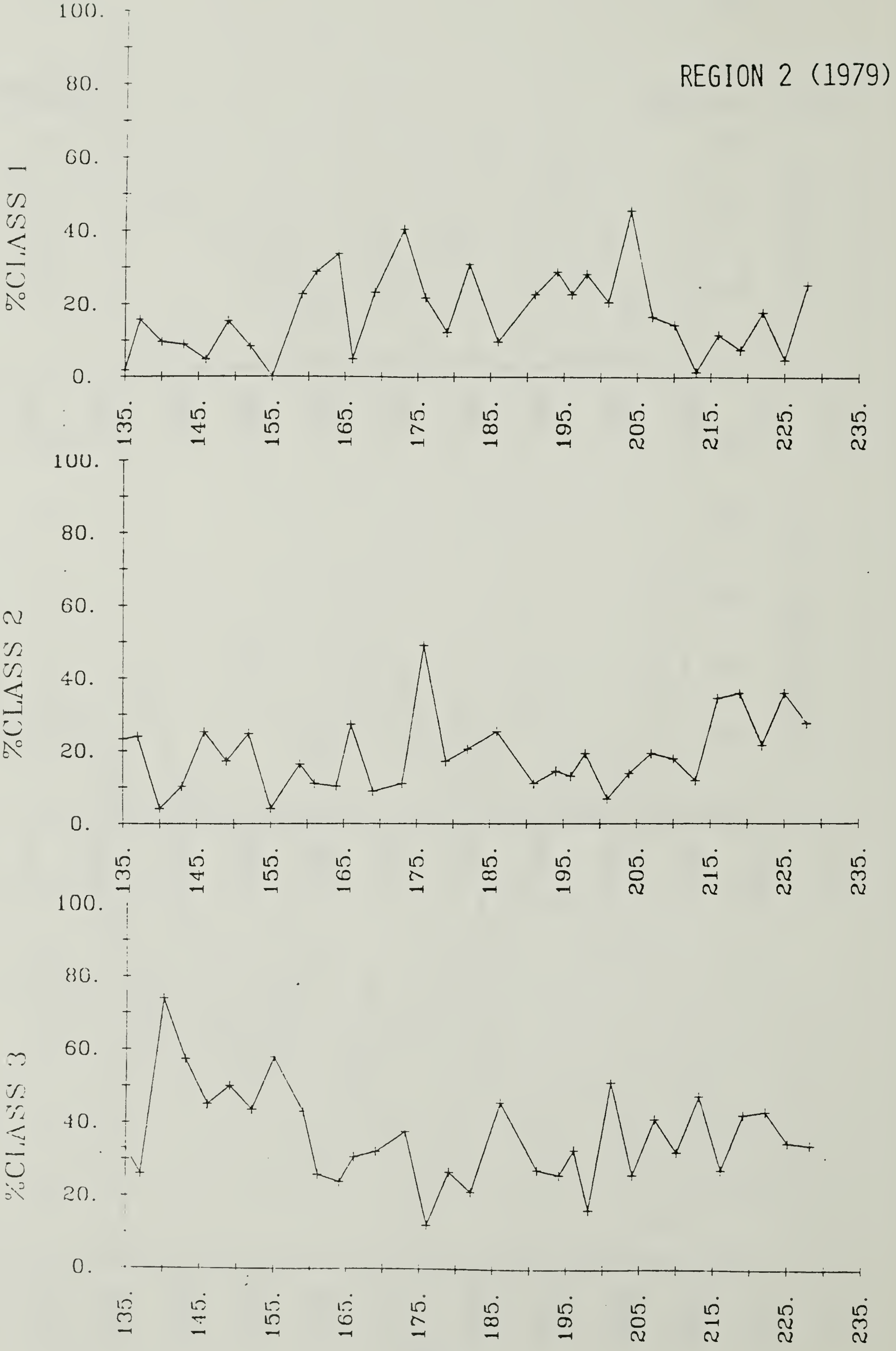

REGION 4 (1977)


REGION 5 (1977)
%CLASS 1
%CLASS 2
%CLASS 3
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

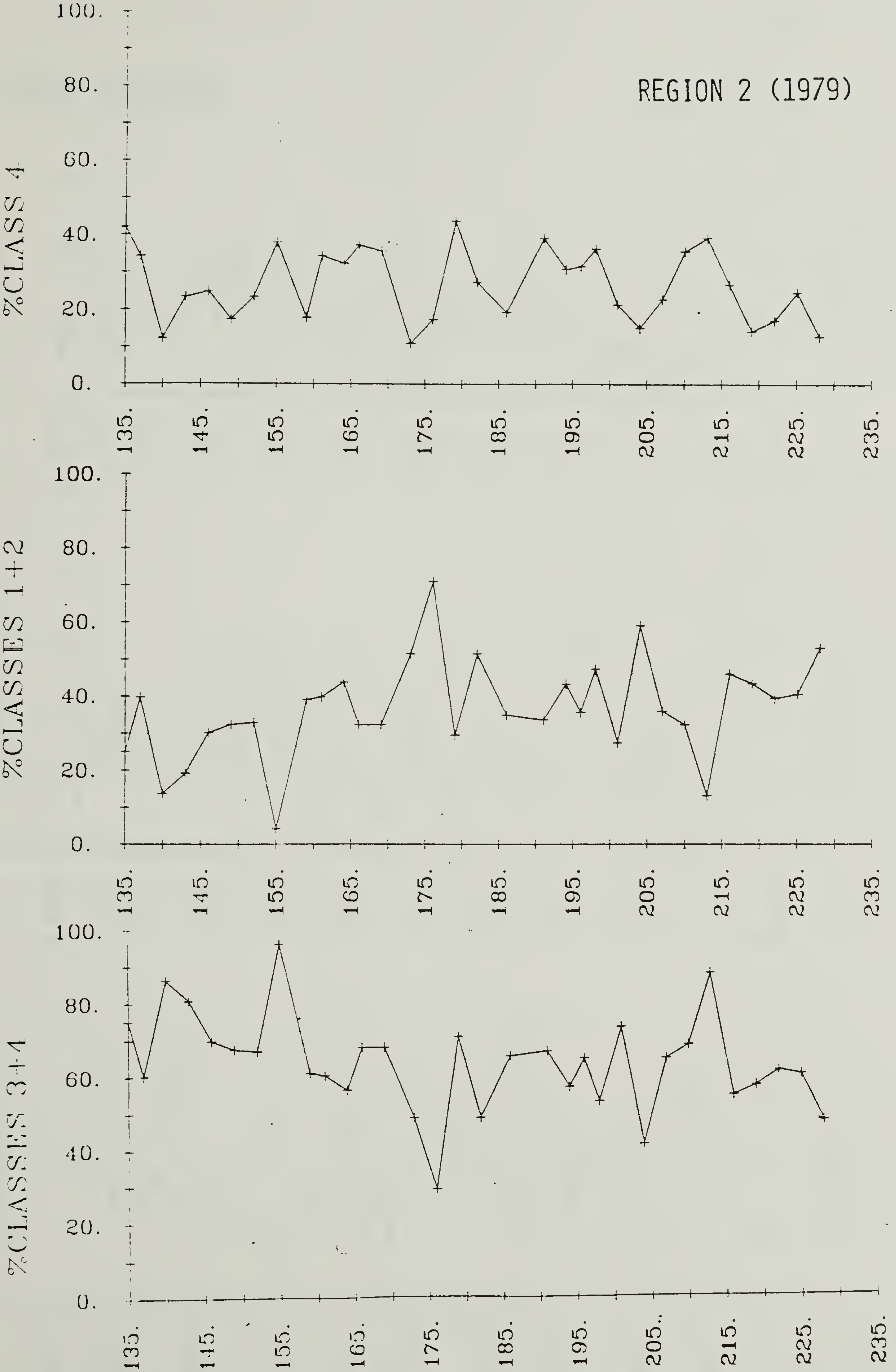

REGION 5 (1977)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

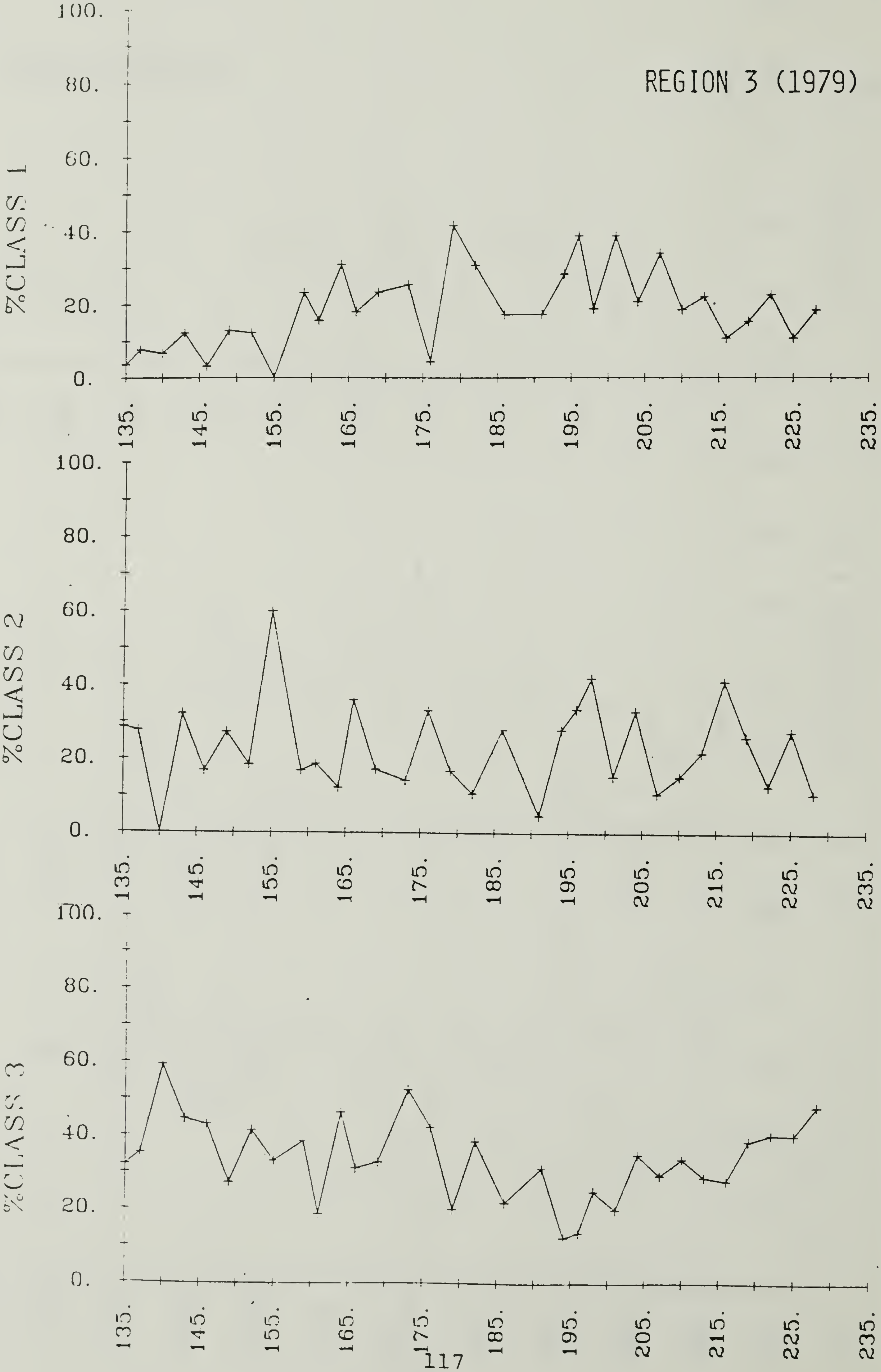

REGION 1 (1979)
%CLASS 1
%CLASS 2
%CLASS 3
100.
80.
60.
40.
20.
0.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

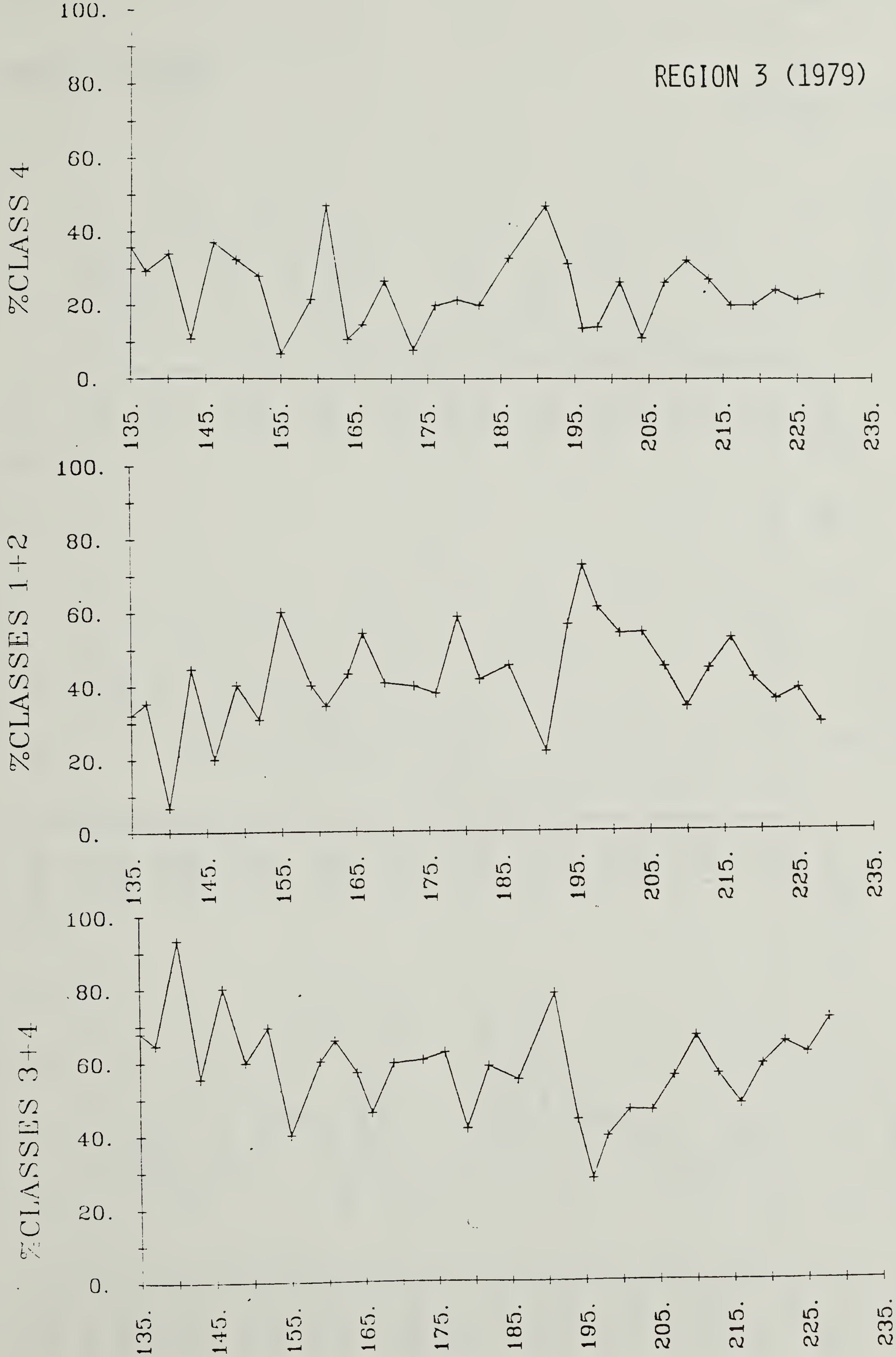

REGION 1 (1979)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.



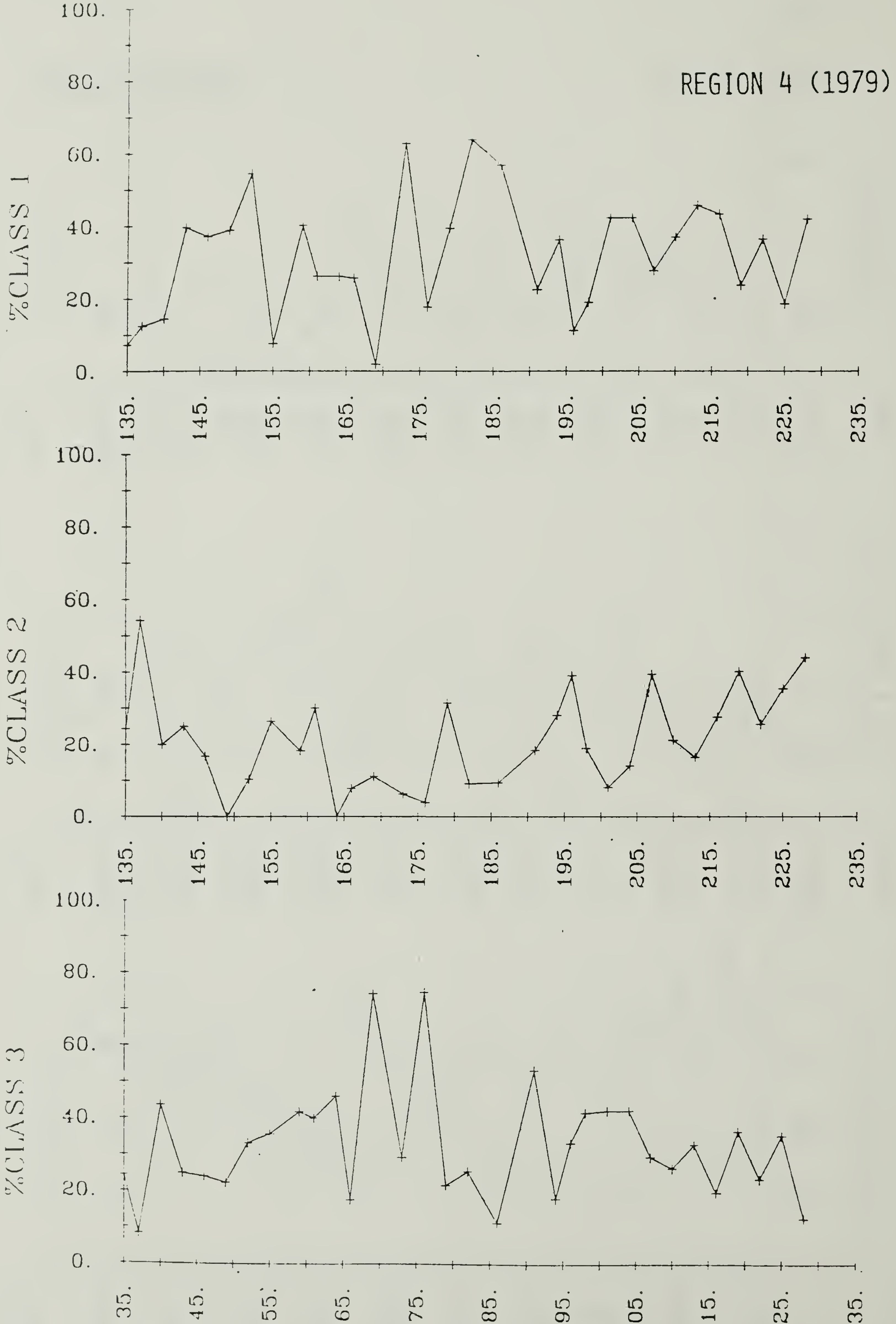
REGION 2 (1979)

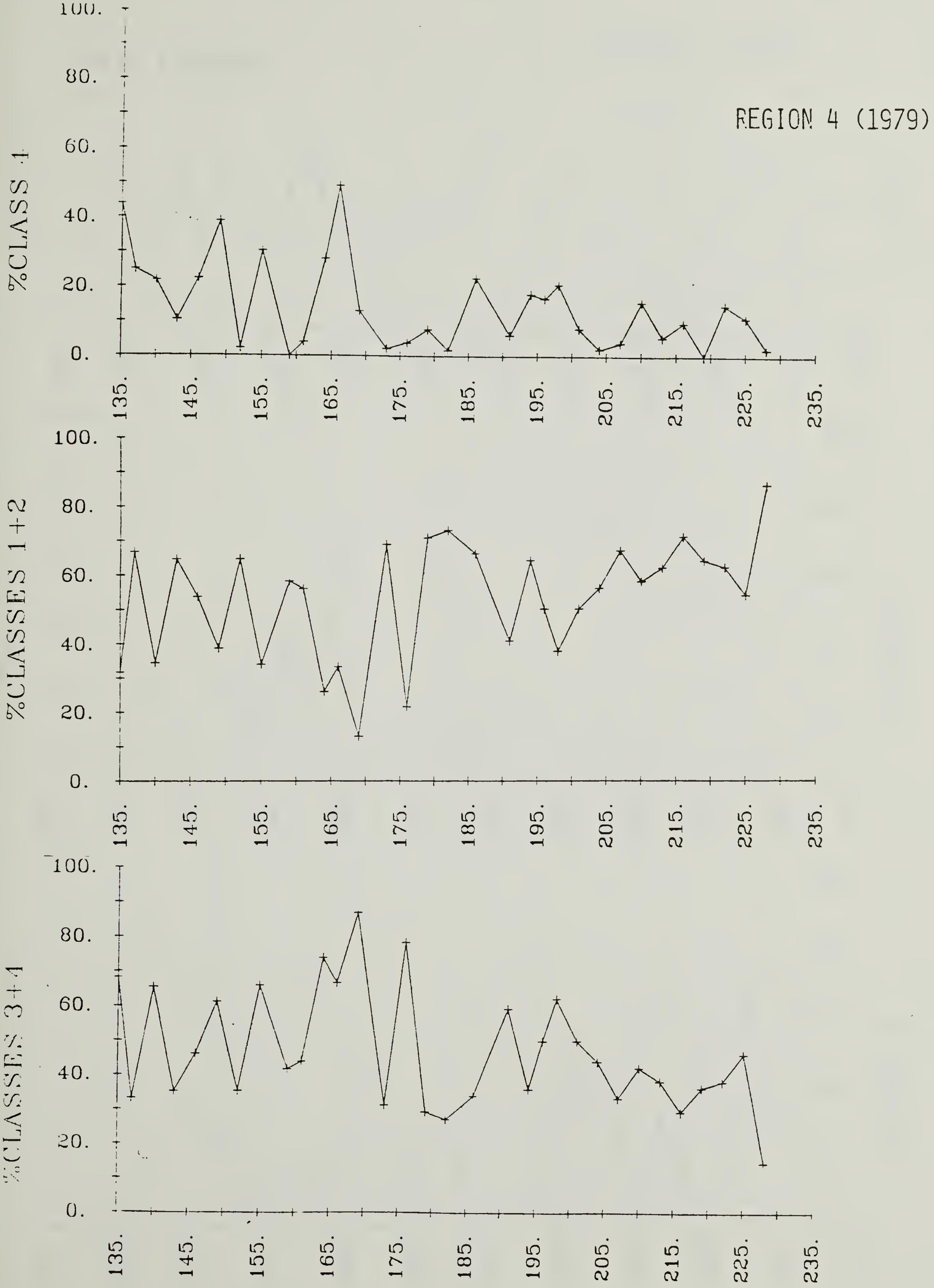

REGION 2 (1979)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

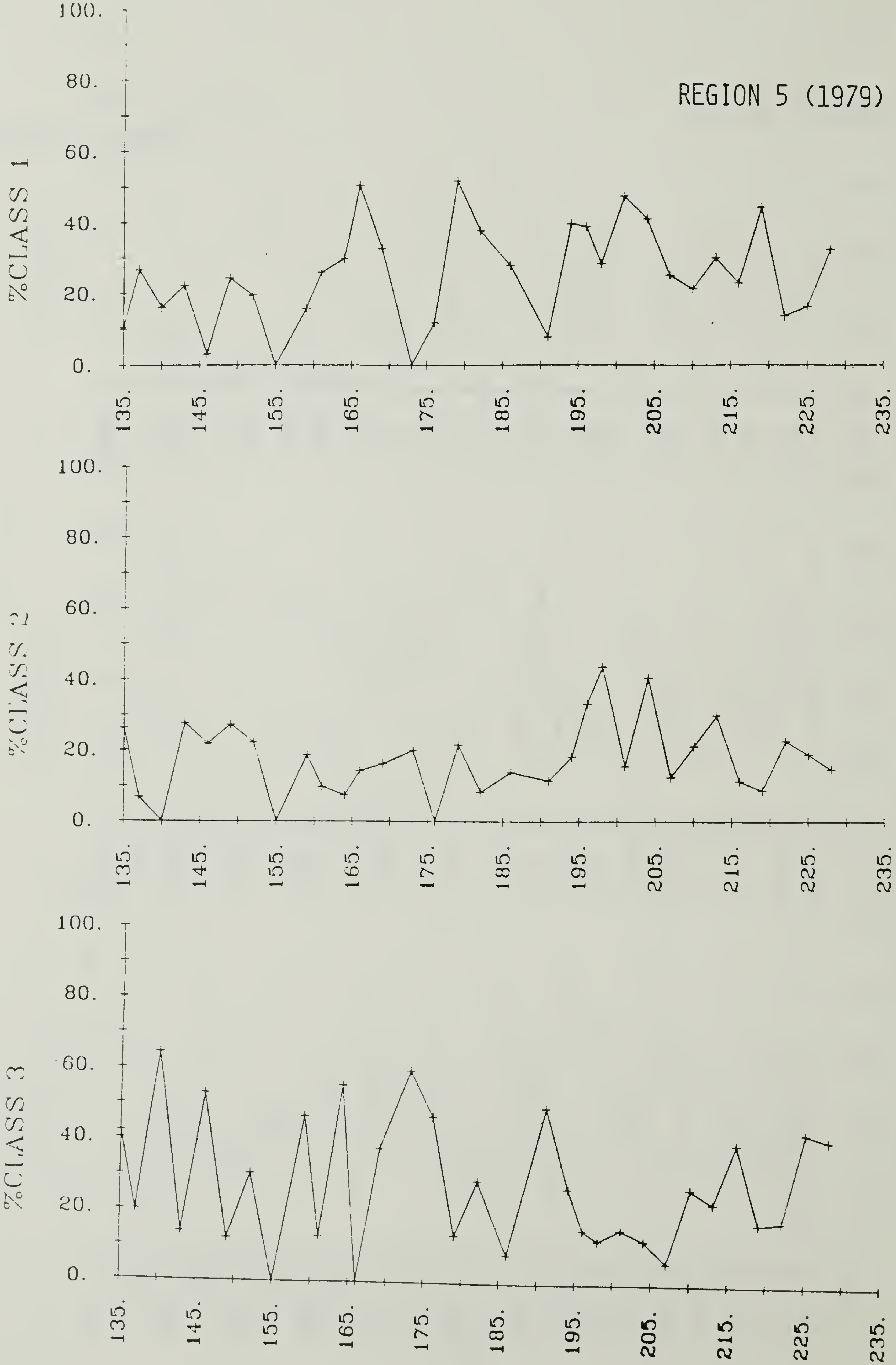

REGION 3 (1979)
%CLASS 1
%CLASS 2
%CLASS 3
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

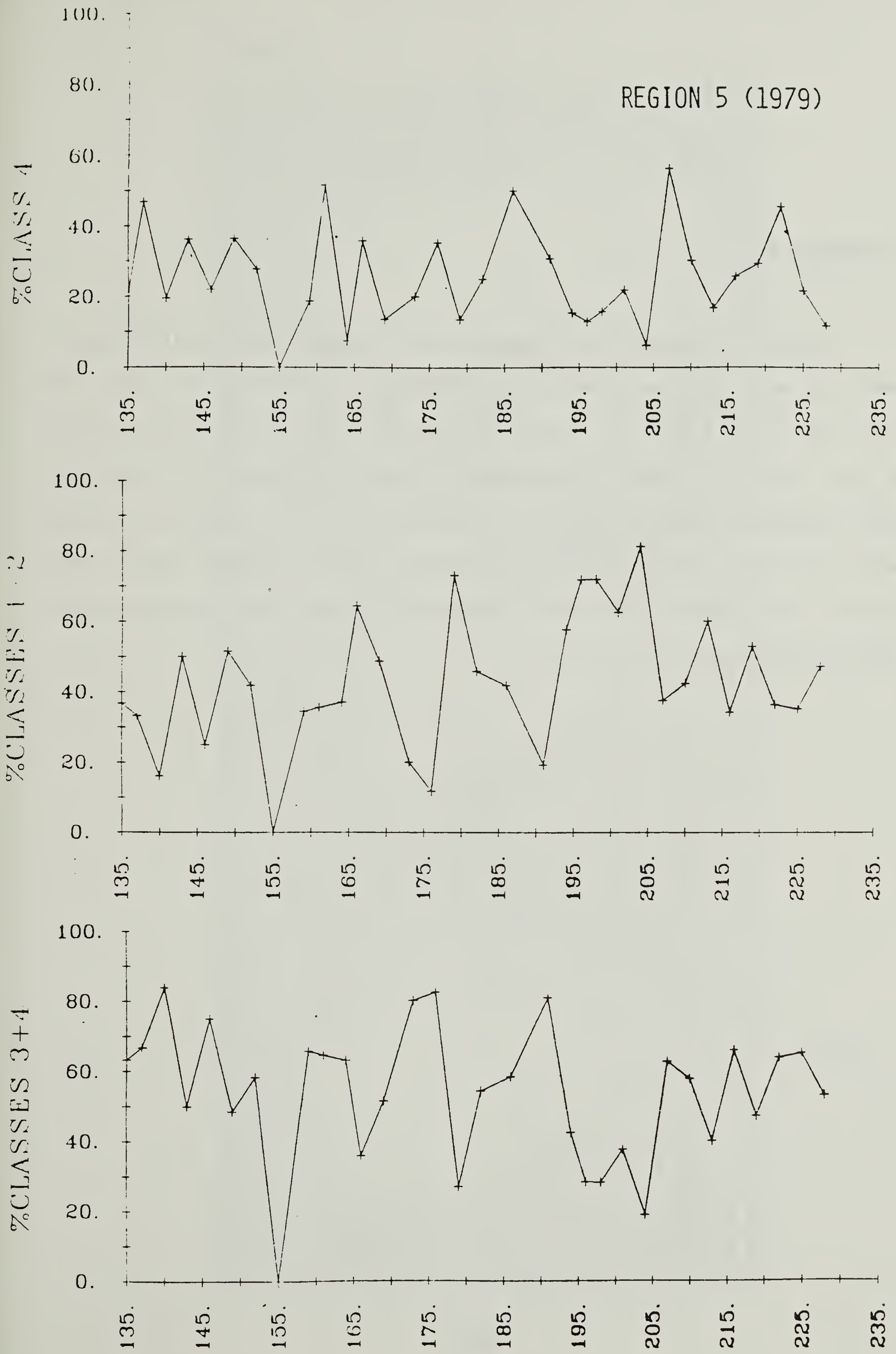

REGION 3 (1979)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

REGION 4 (1979)




REGION 4 (1979)

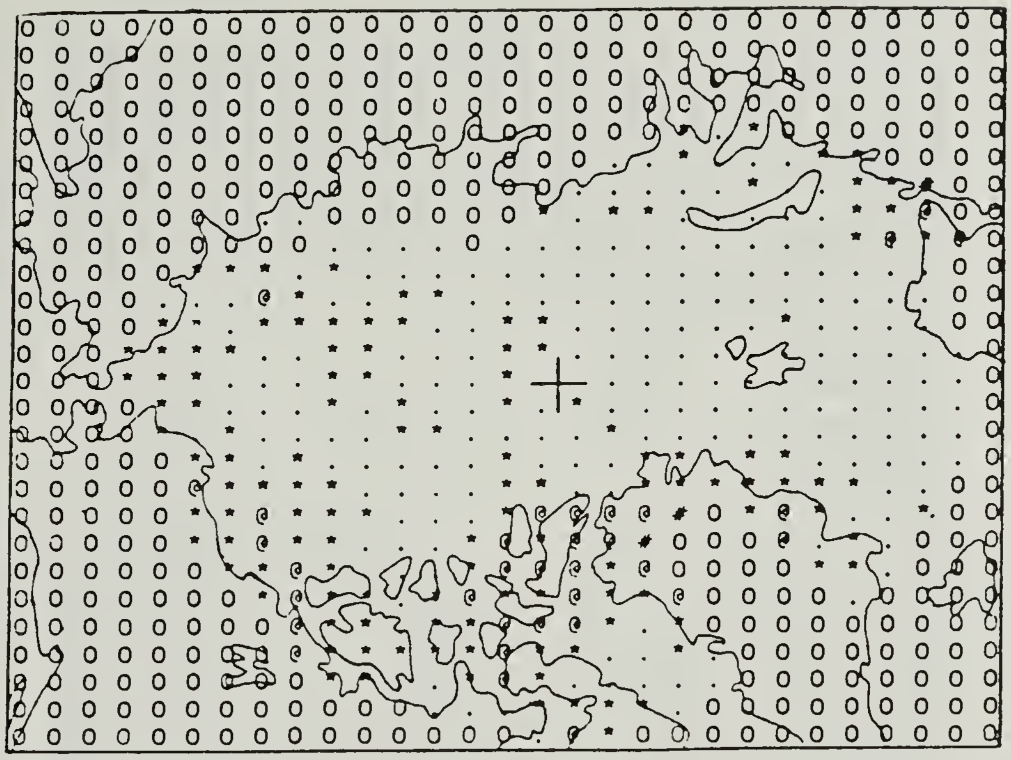

REGION 5 (1979)
%CLASS 1
%CLASS 2
%CLASS 3
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.


REGION 5 (1979)
%CLASS 4
%CLASSES 1+2
%CLASSES 3+4
0.
20.
40.
60.
80.
100.
135.
145.
155.
165.
175.
185.
195.
205.
215.
225.
235.

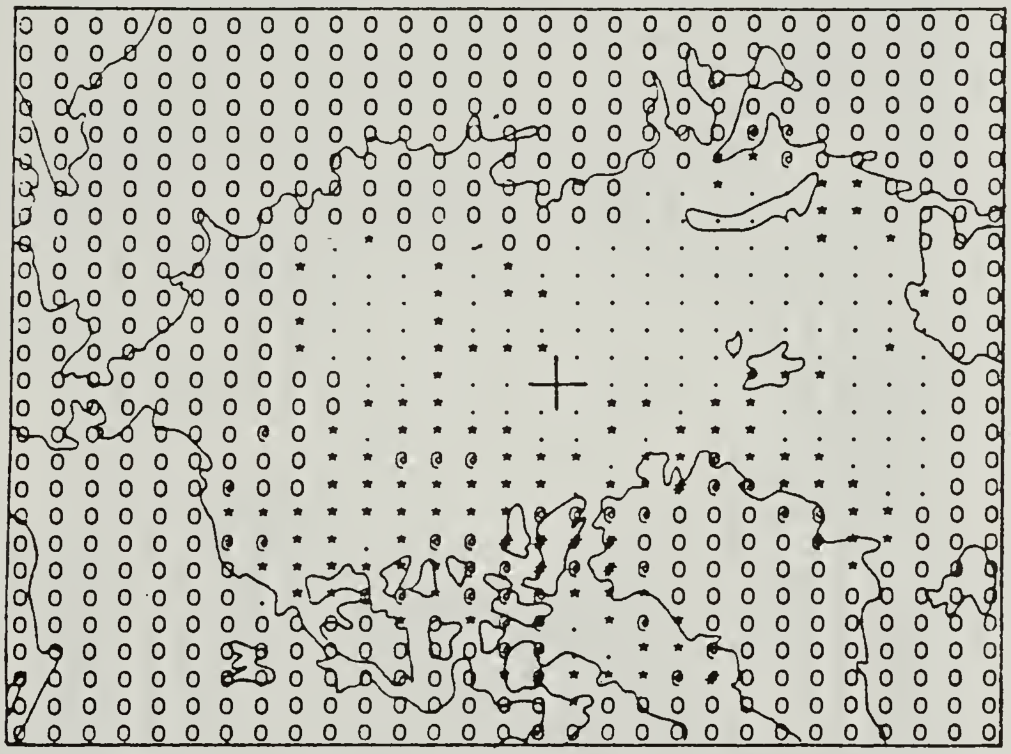
APPENDIX 5.

Percent frequency of cloud cover classes 1-4, individually and 1+2 and 3+4 combined, averaged over the months of June and July 1977 and May 15 - August 15, 1979. For a given grid cell a dot indicates that a particular class is plotted in 0-25% of the available daily charts in the month, a * 26-50%, @ 51-75% and # 76-100%. Only those grid cells where at least 70% of the charts had charted data are plotted. Cells with insufficient data are marked with a zero.

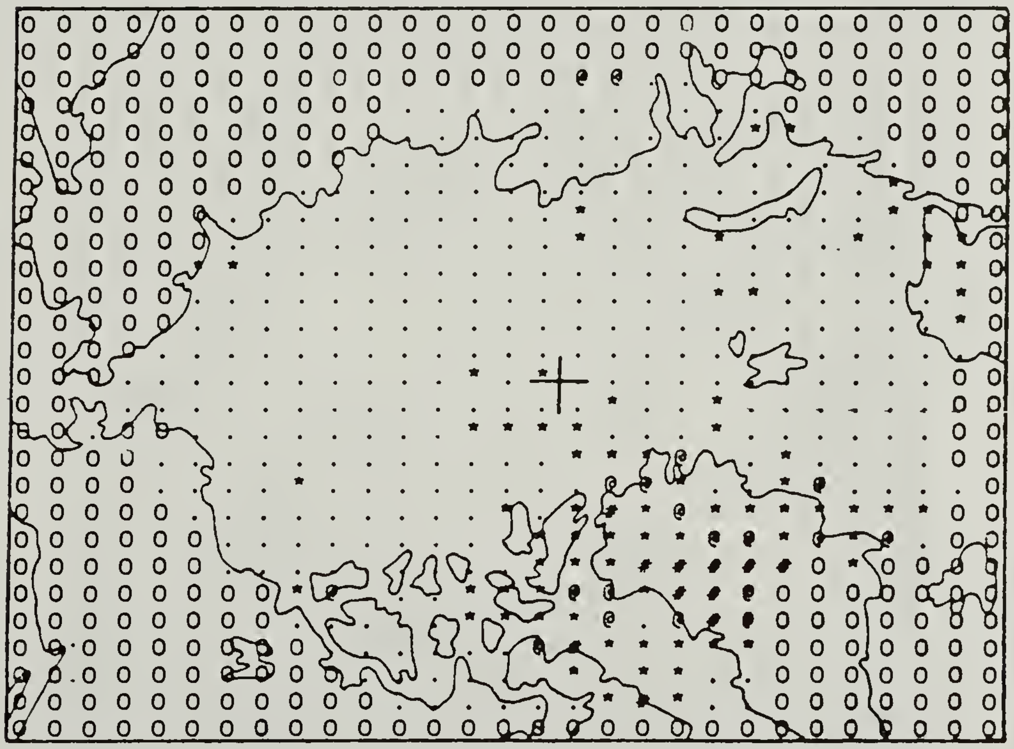
CLASS 1



6/77

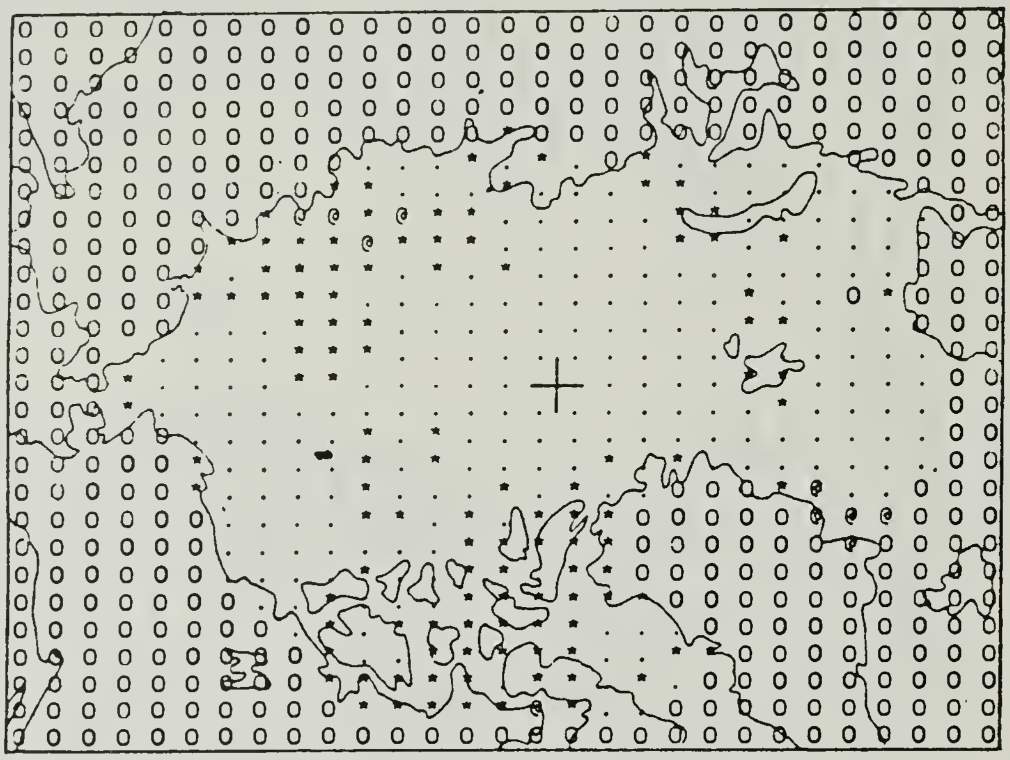


7/77

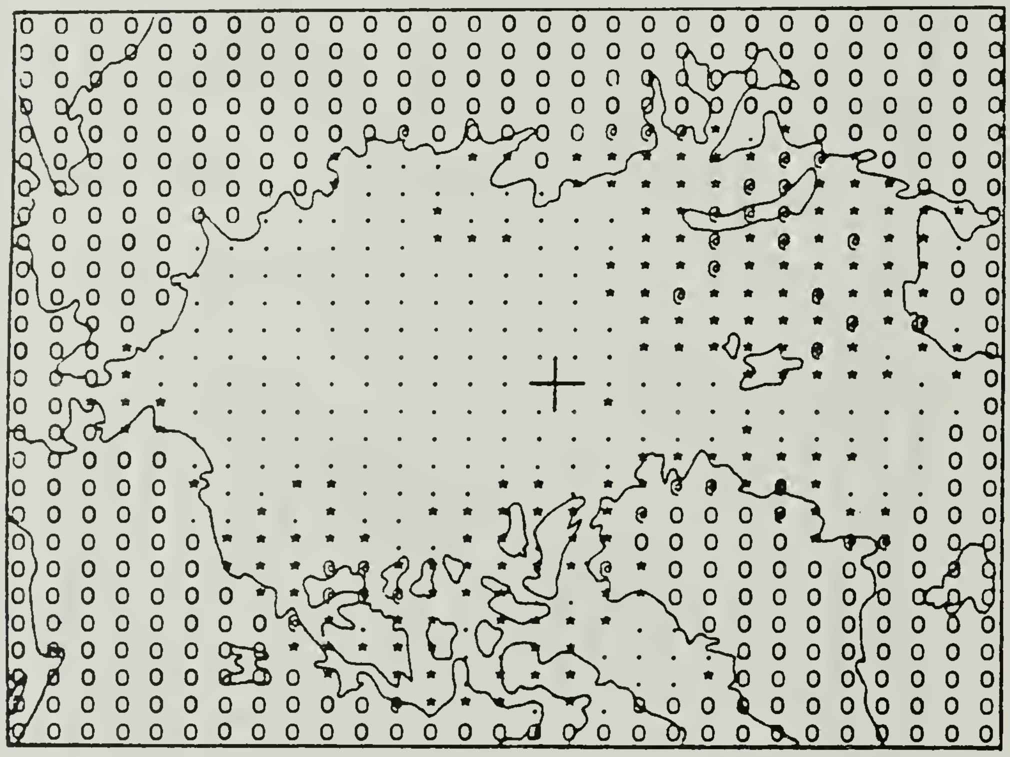


5/79

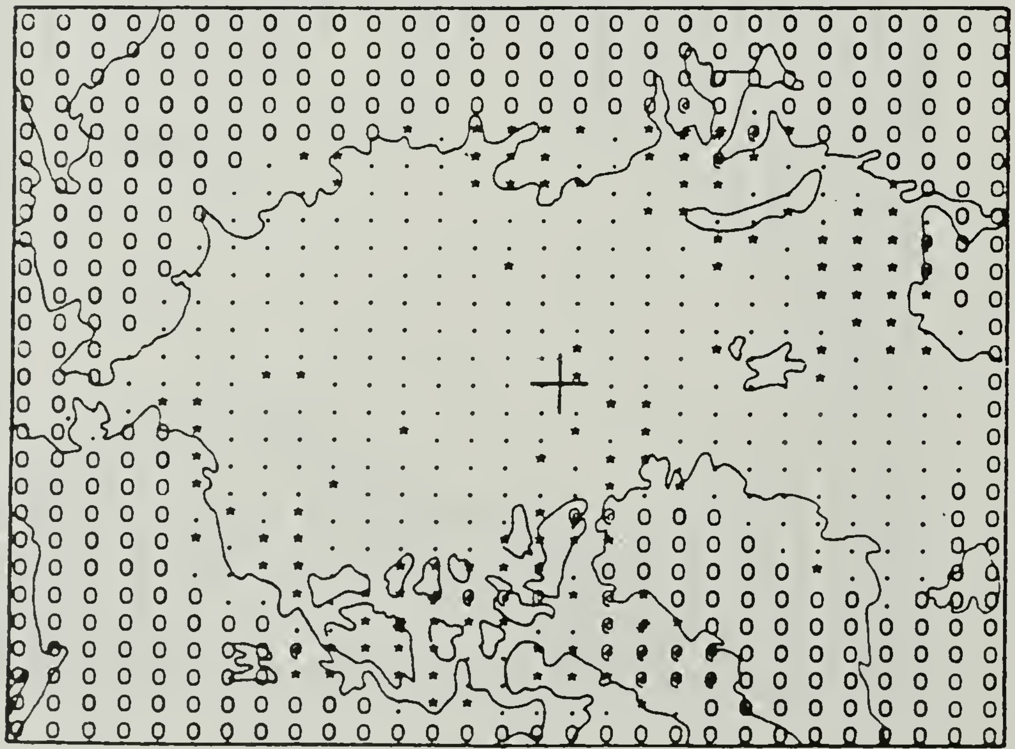
CLASS 1



6/79

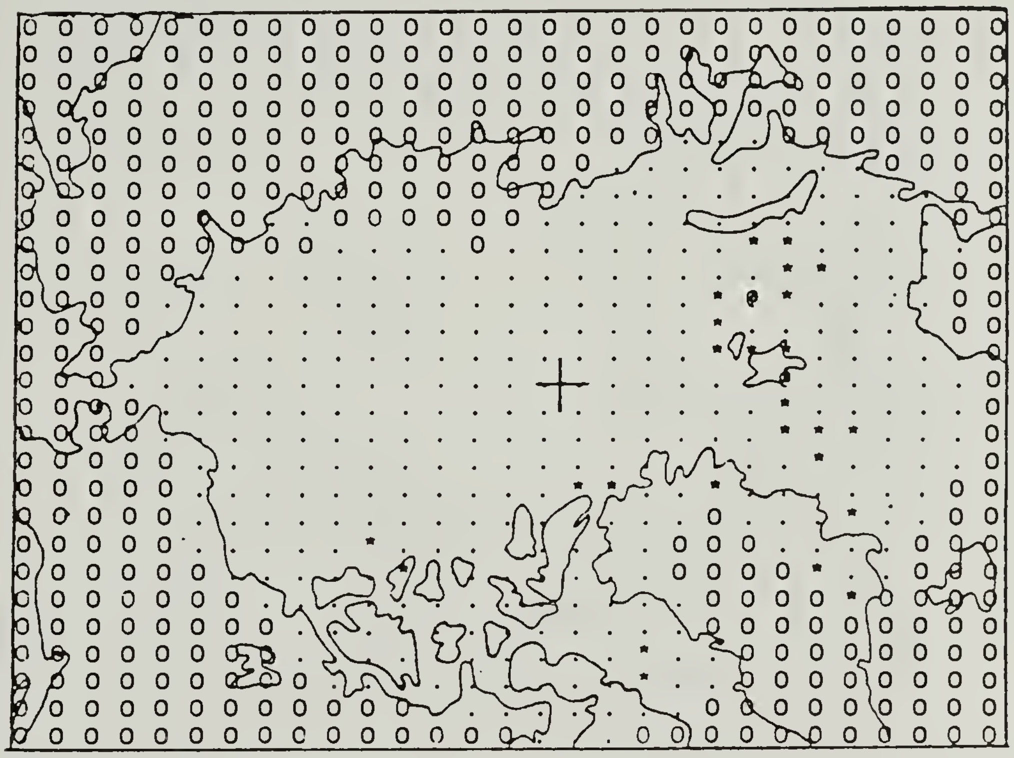


7/79

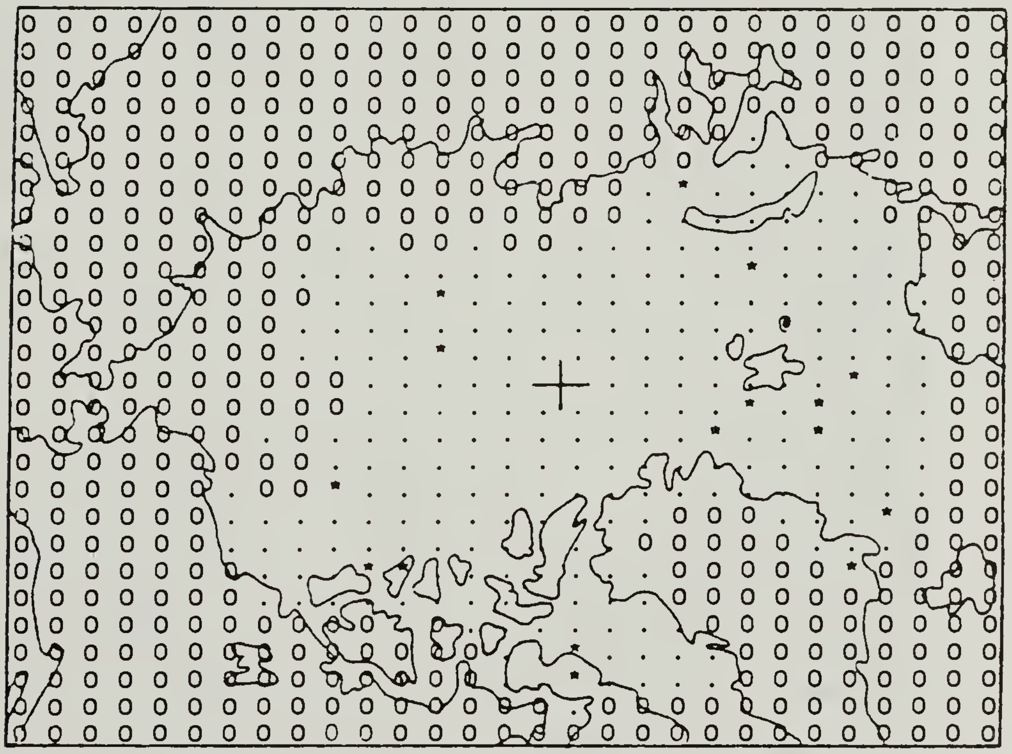


8/79

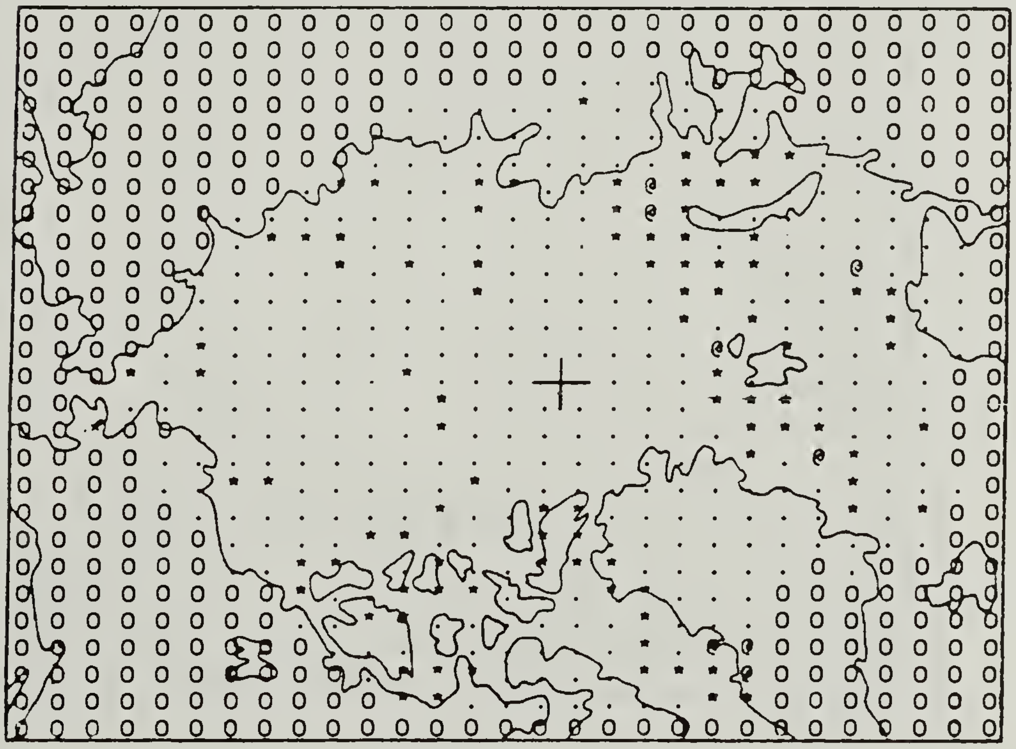
CLASS 2



6/77

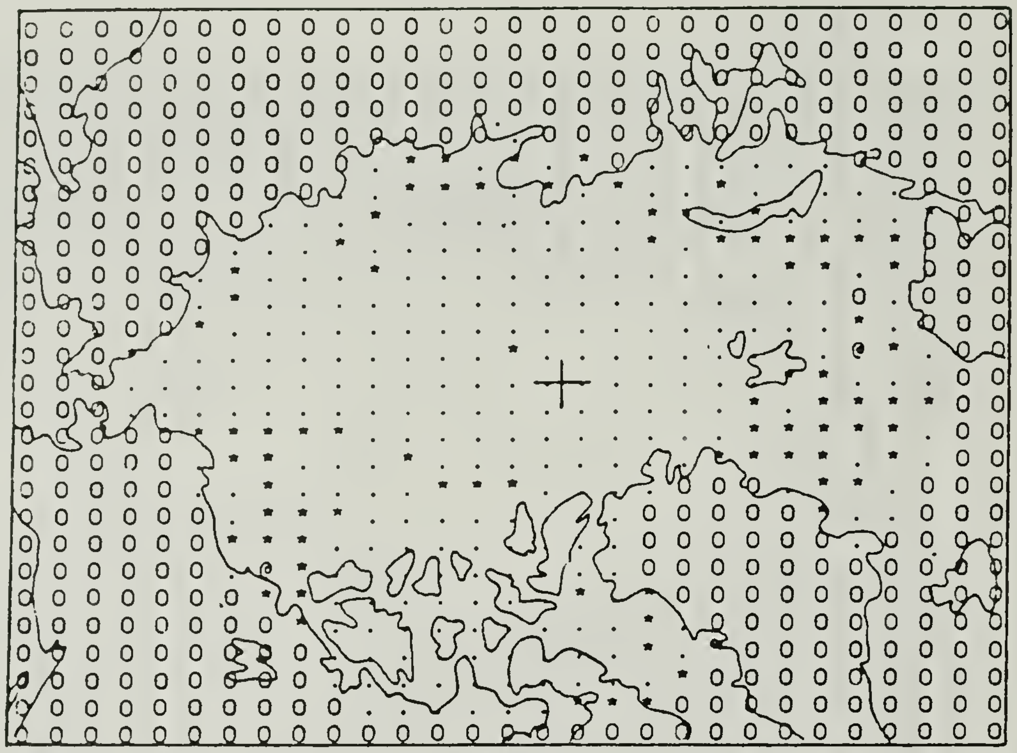


7/77

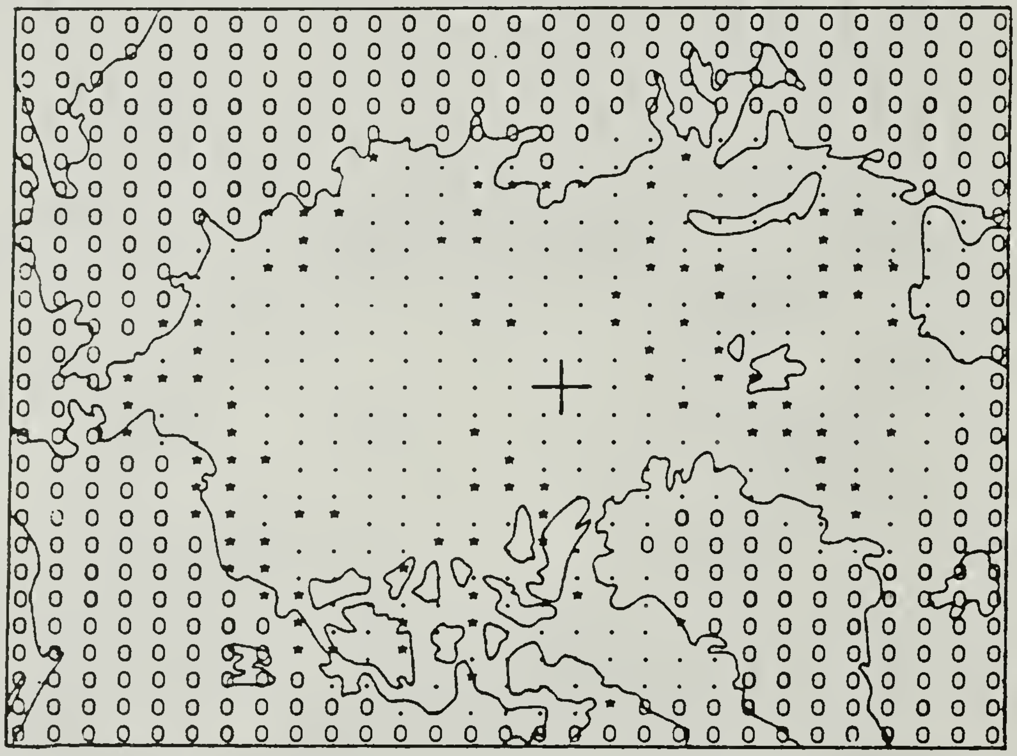


5/79

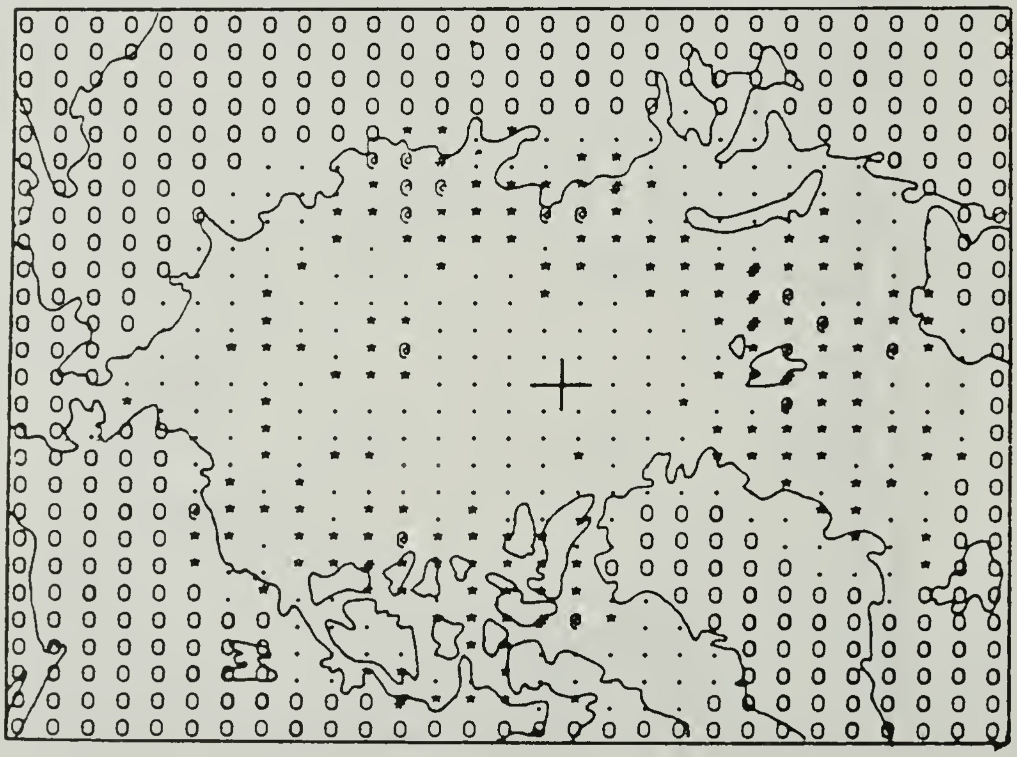
CLASS 2



6/79

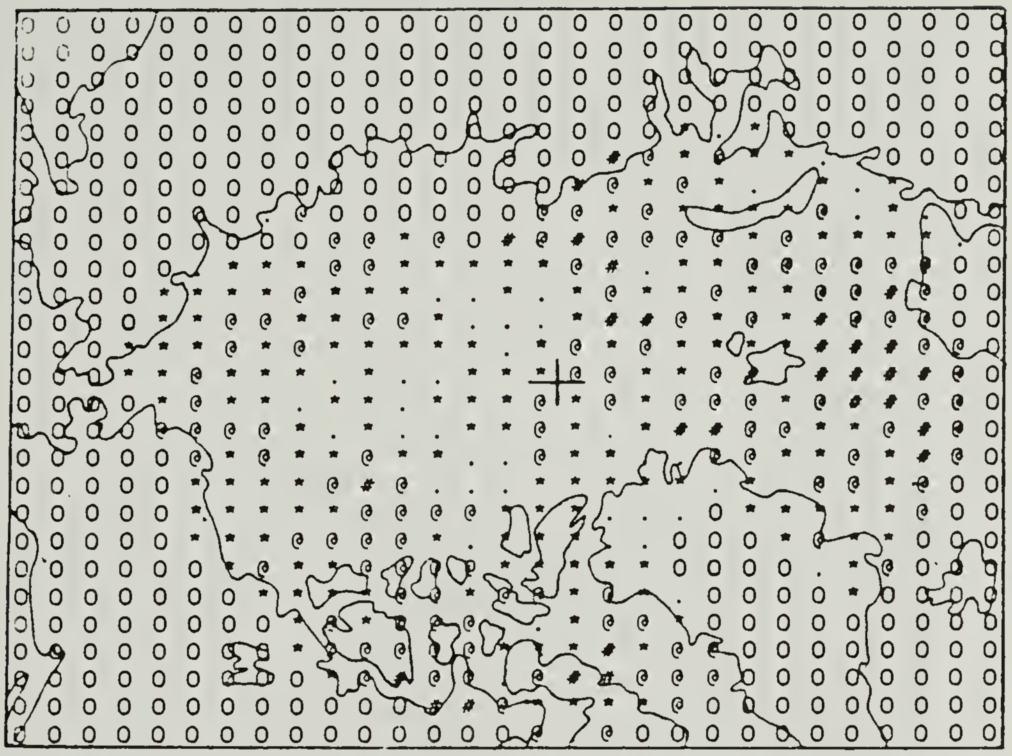


7/79

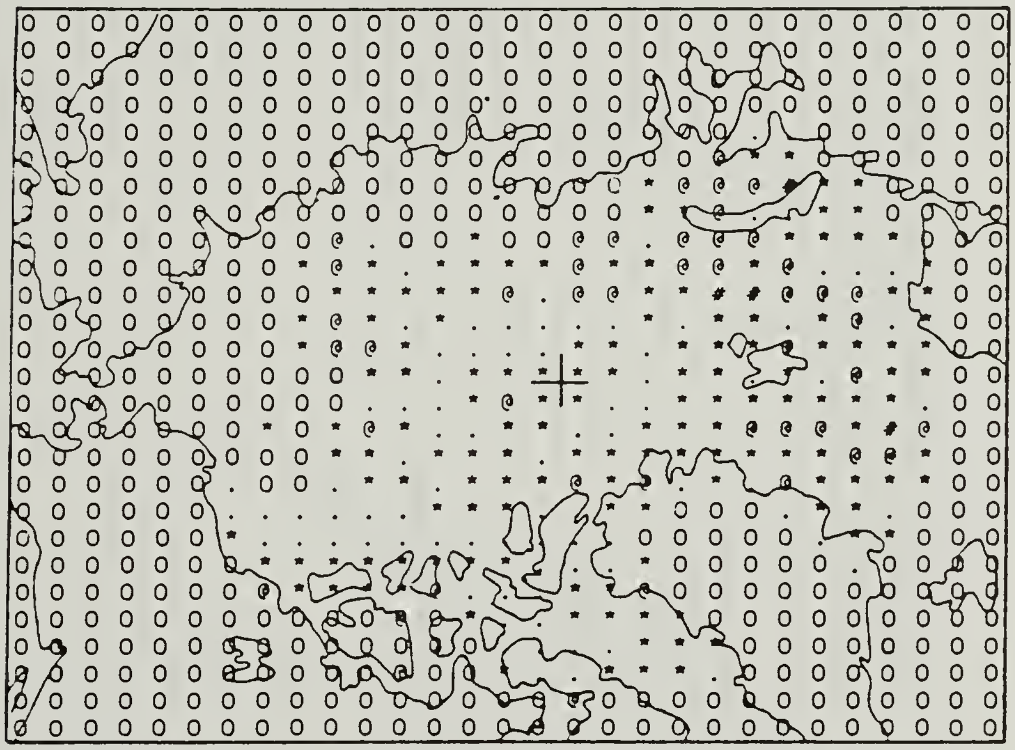


8/79

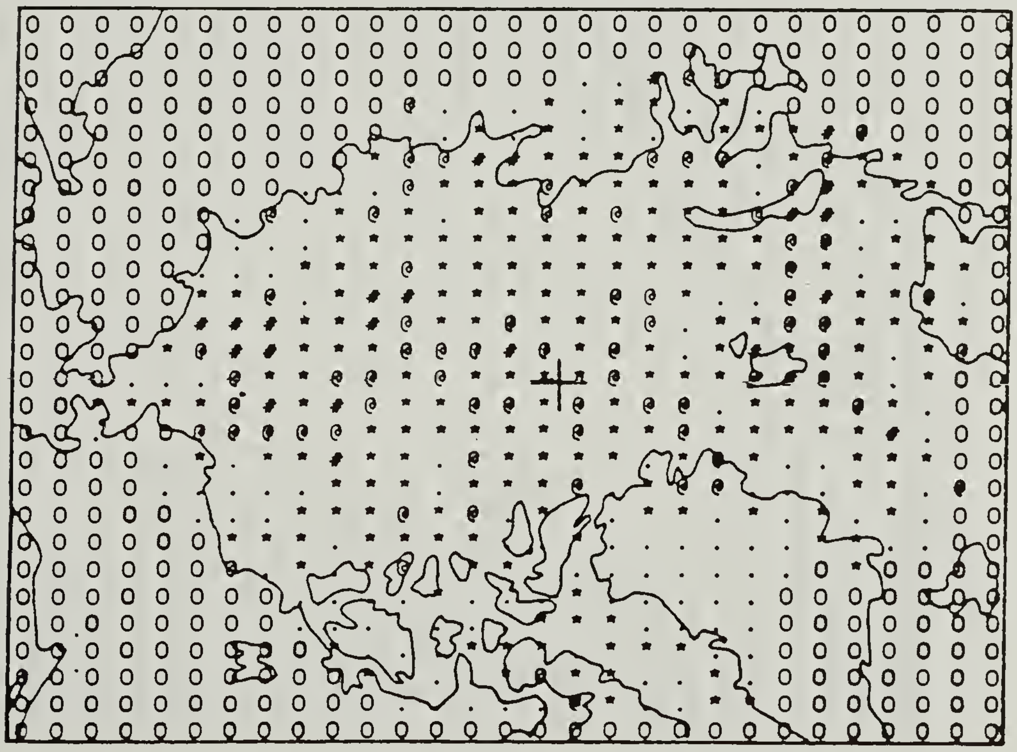
CLASS 3



6/77

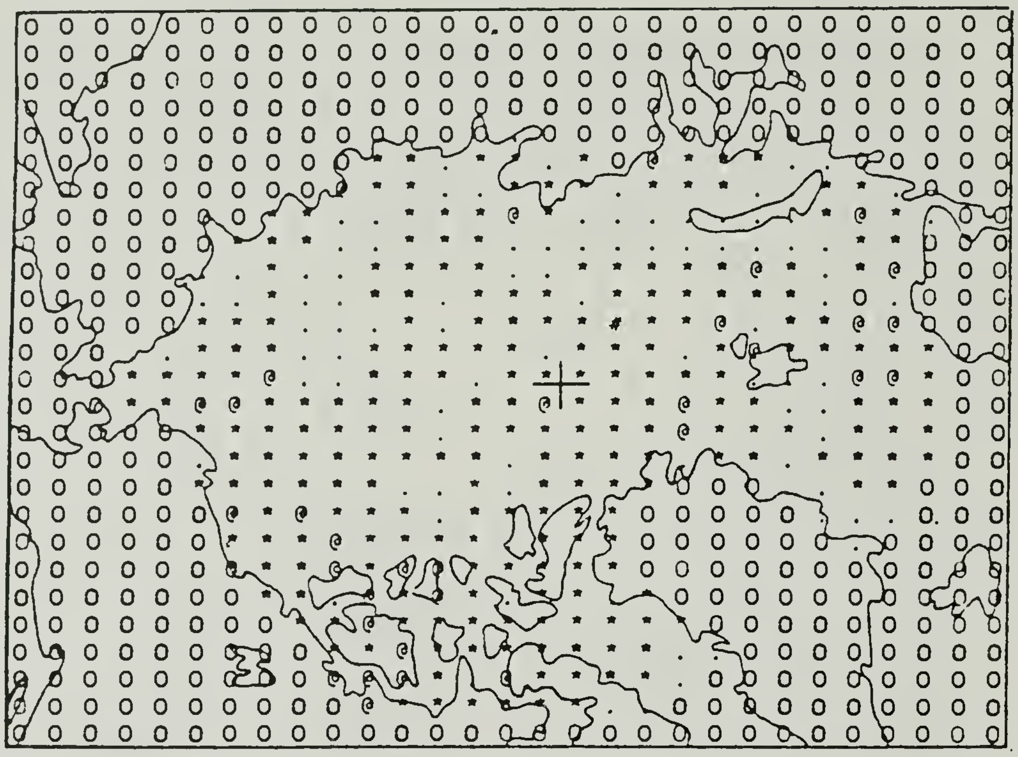


7/77

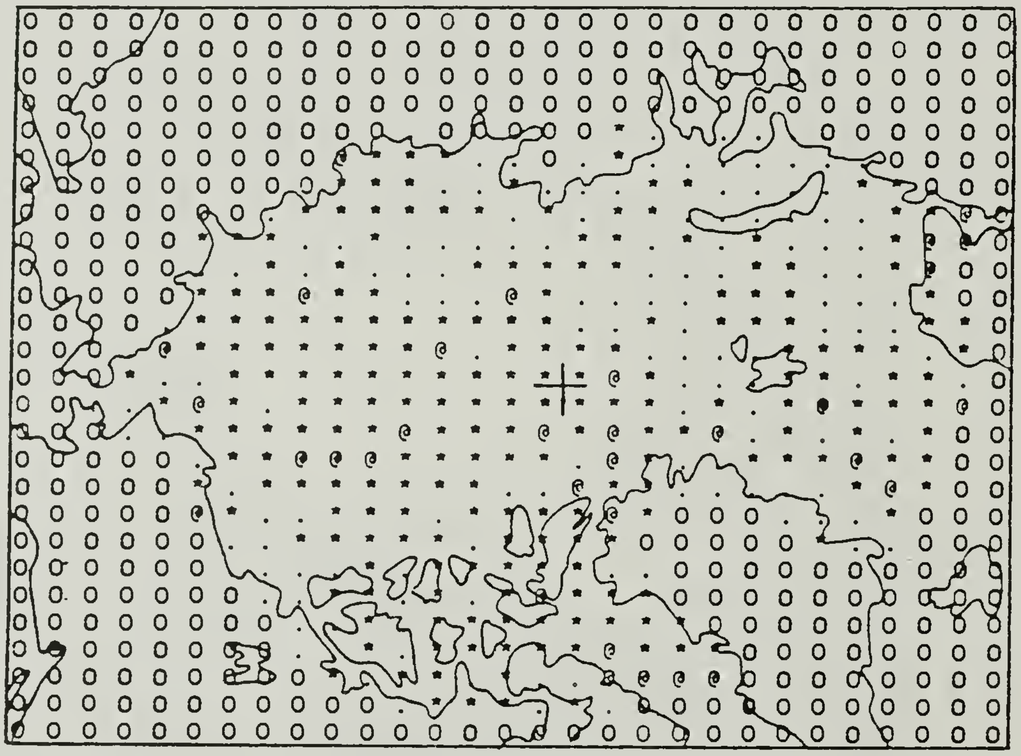


5/79

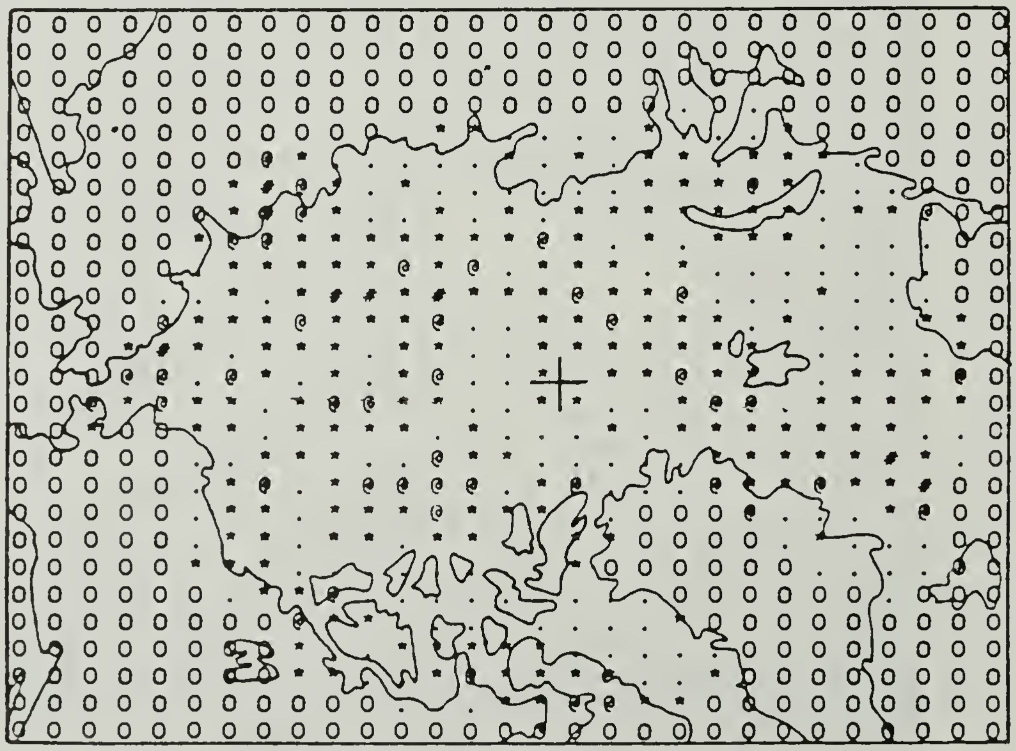
CLASS 3



6/79

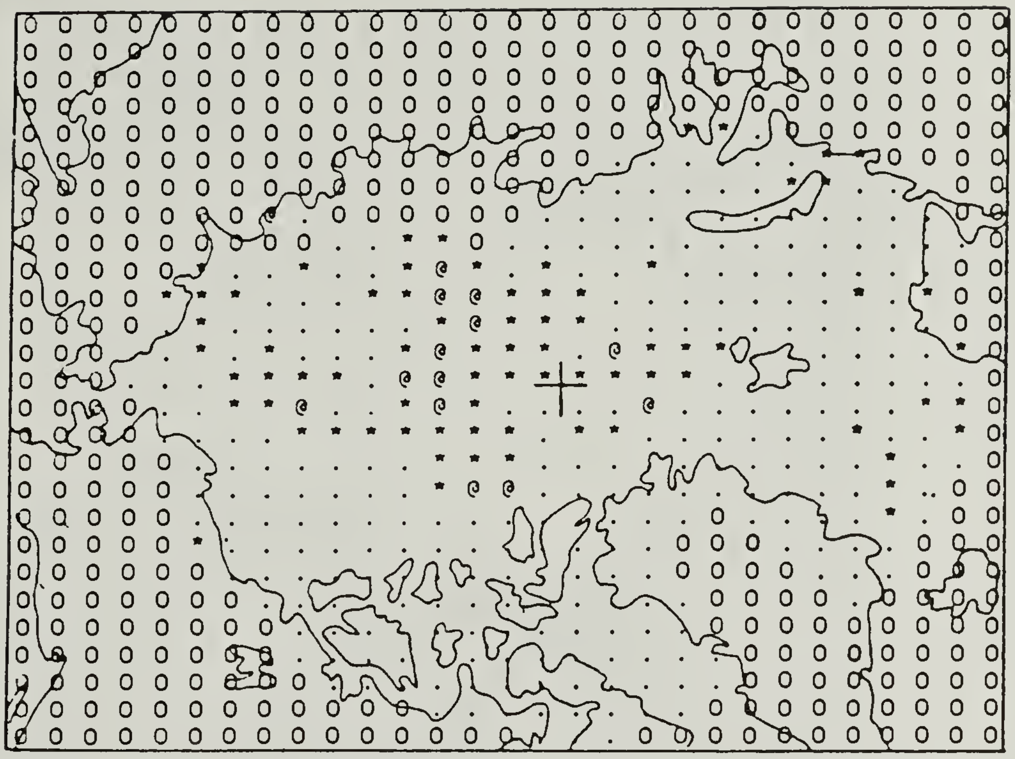


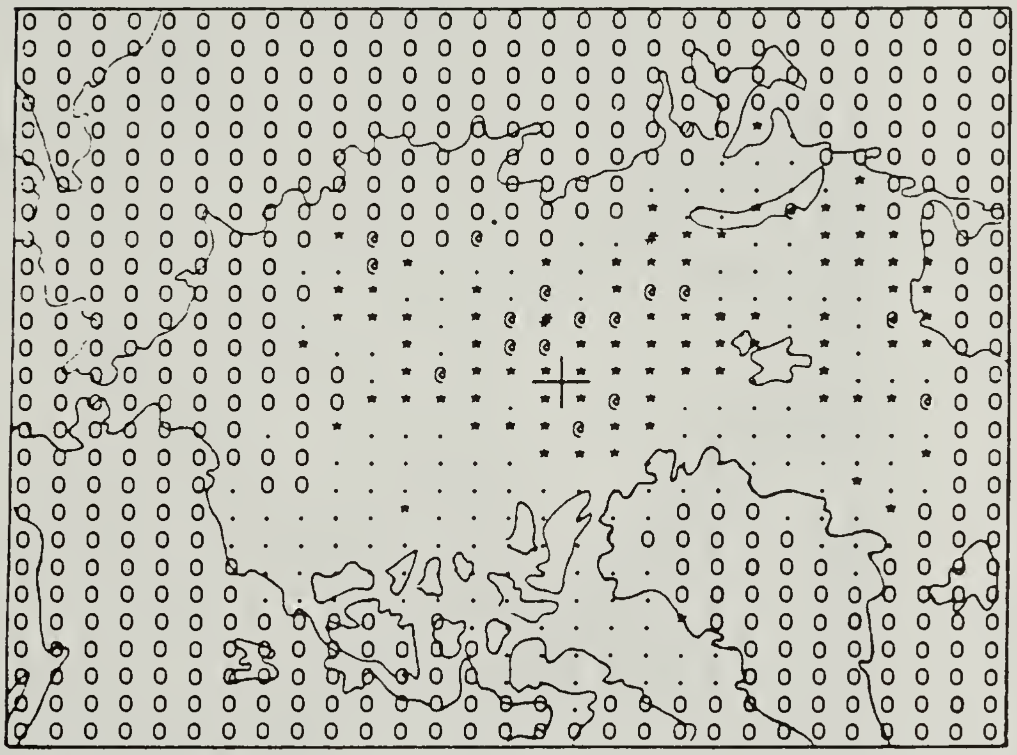
7/79

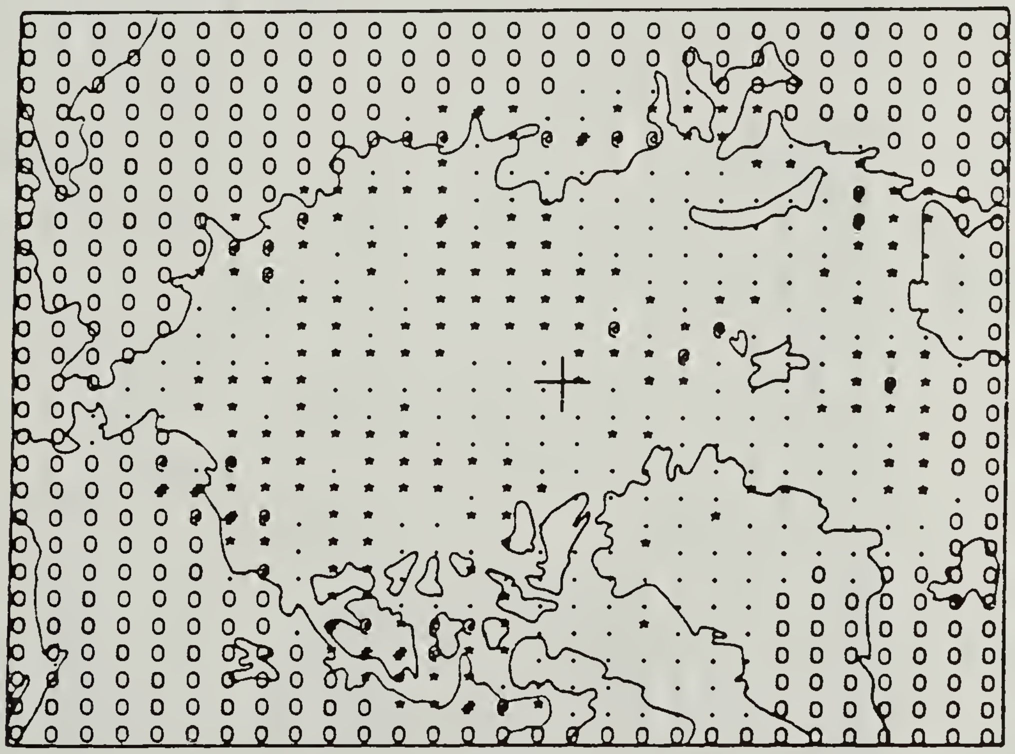


8/79

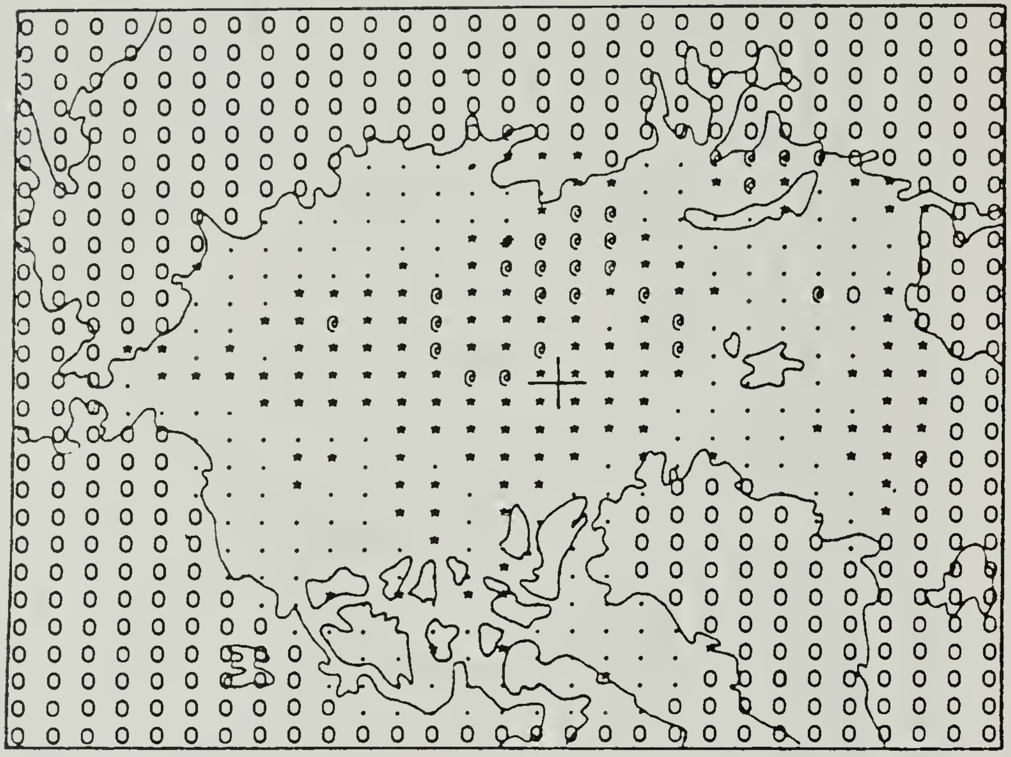
CLASS 4


6/77

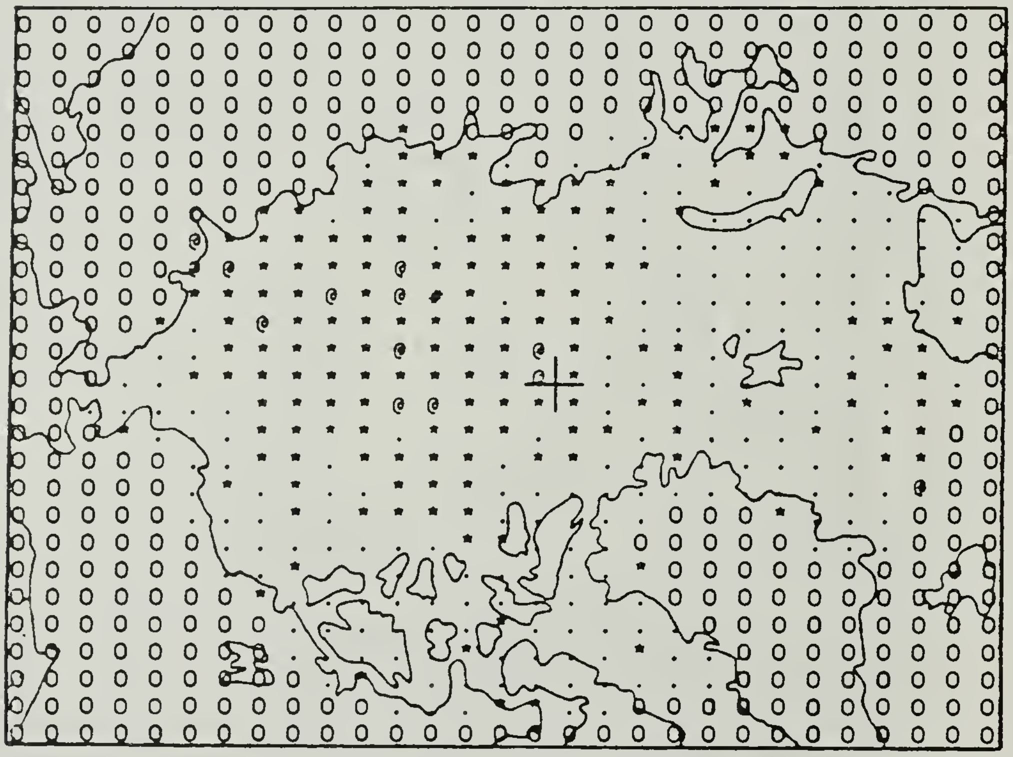

7/77


5/79

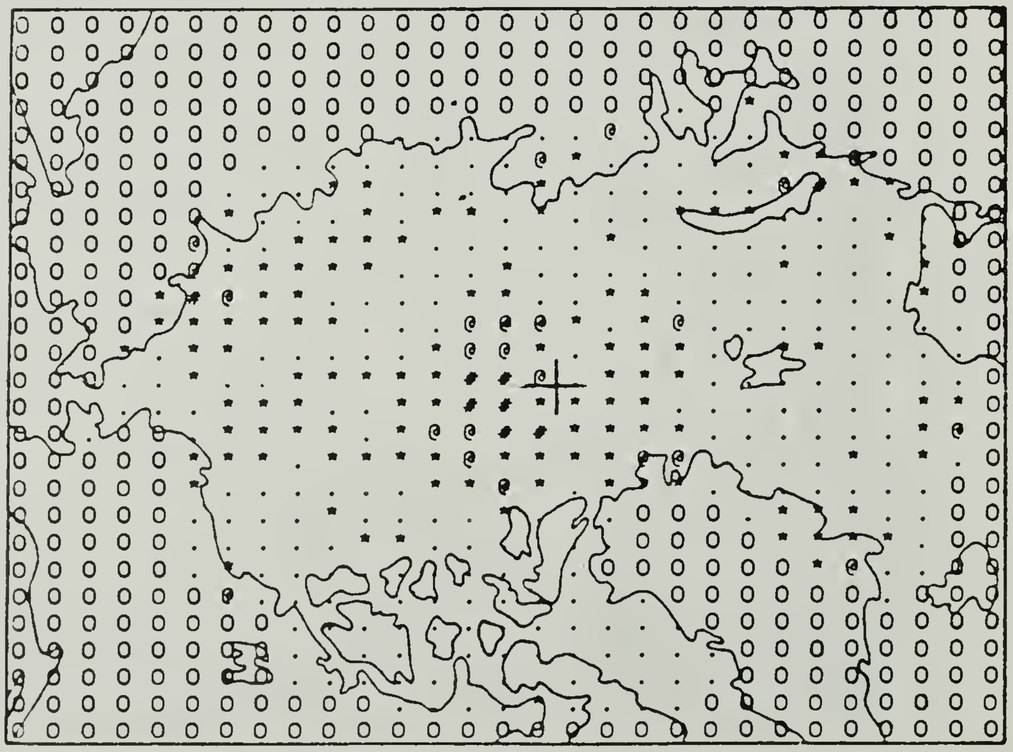
CLASS 4



6/79

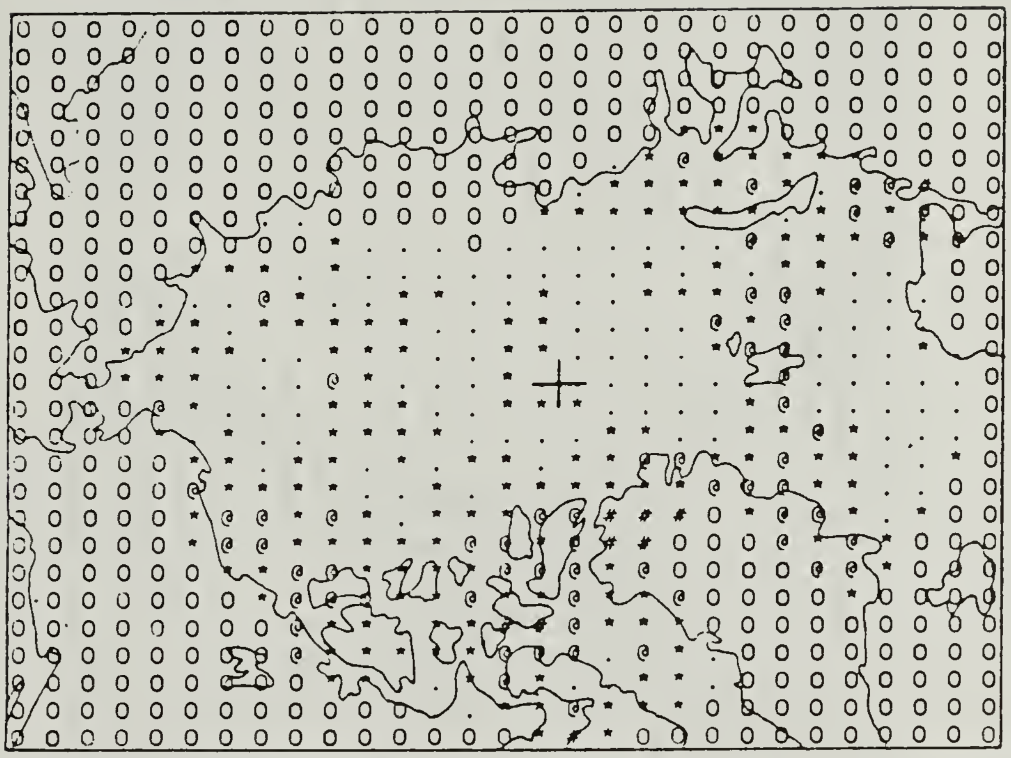


7/79

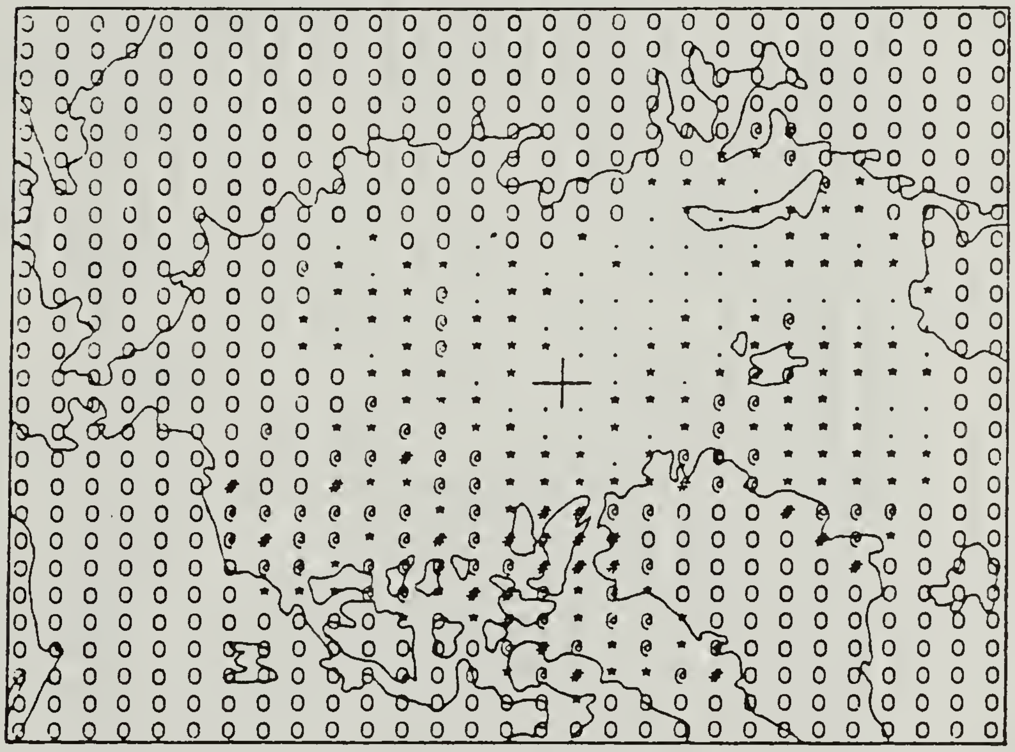


8/79

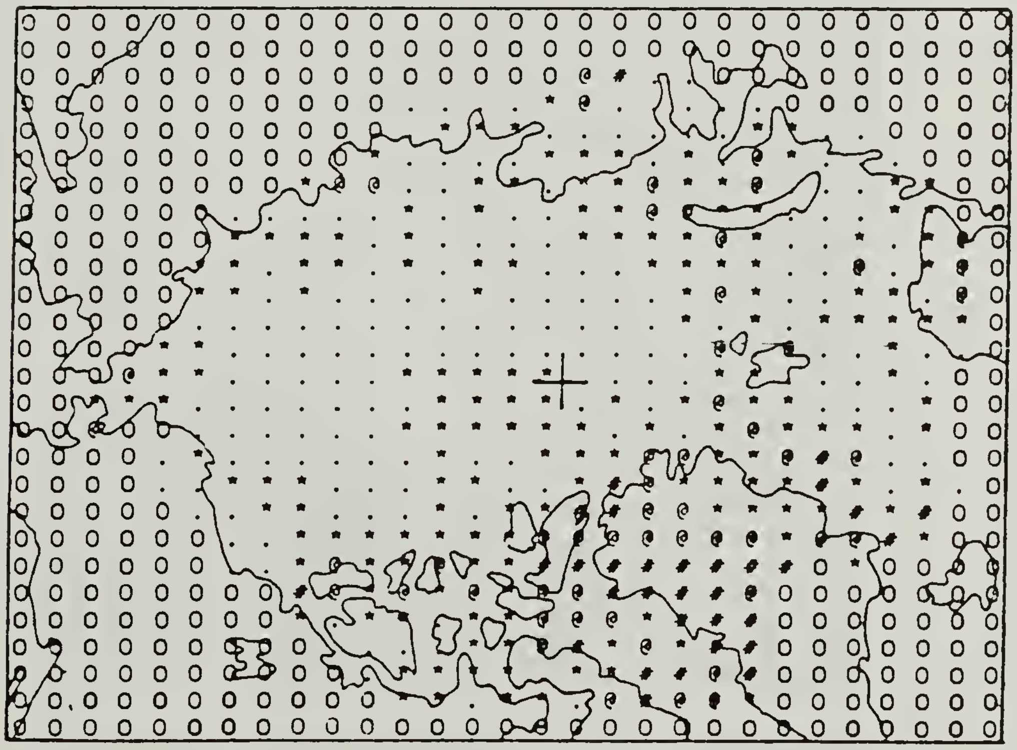
CLASSES 1+2



6/77

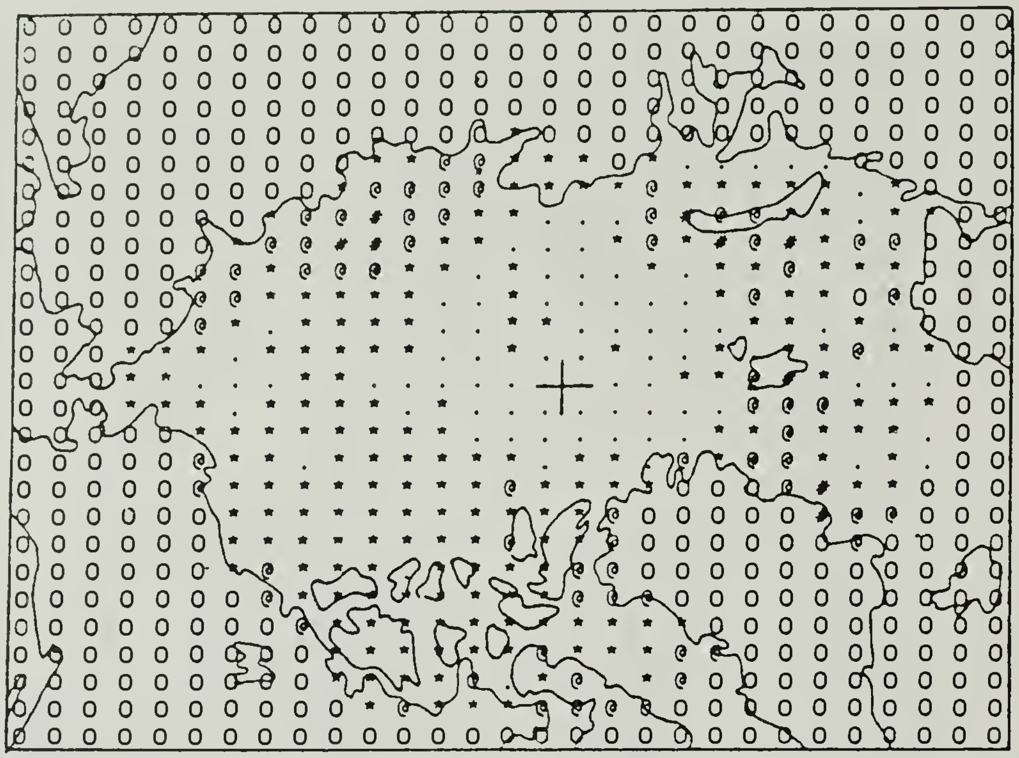


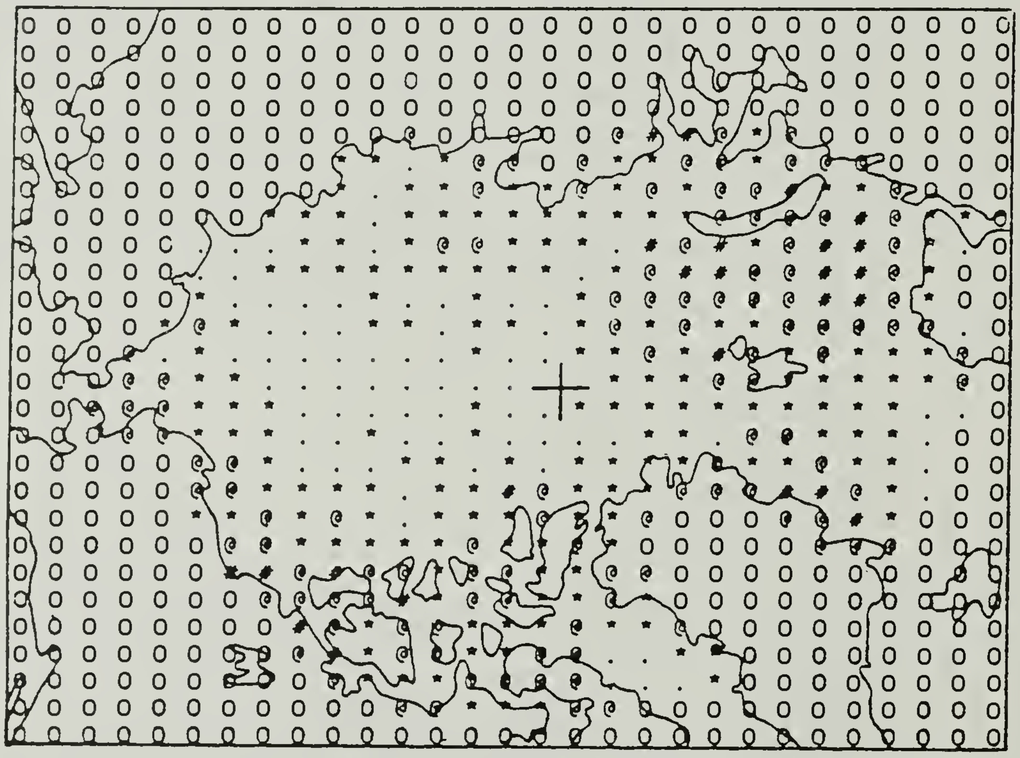
7/77

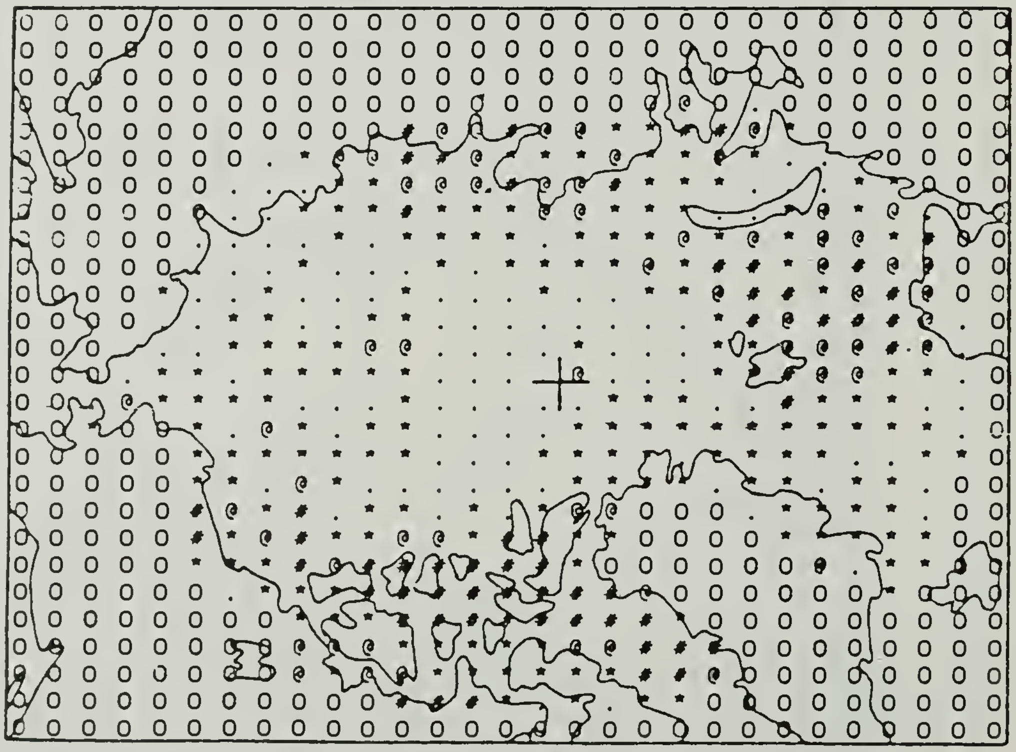


5/79

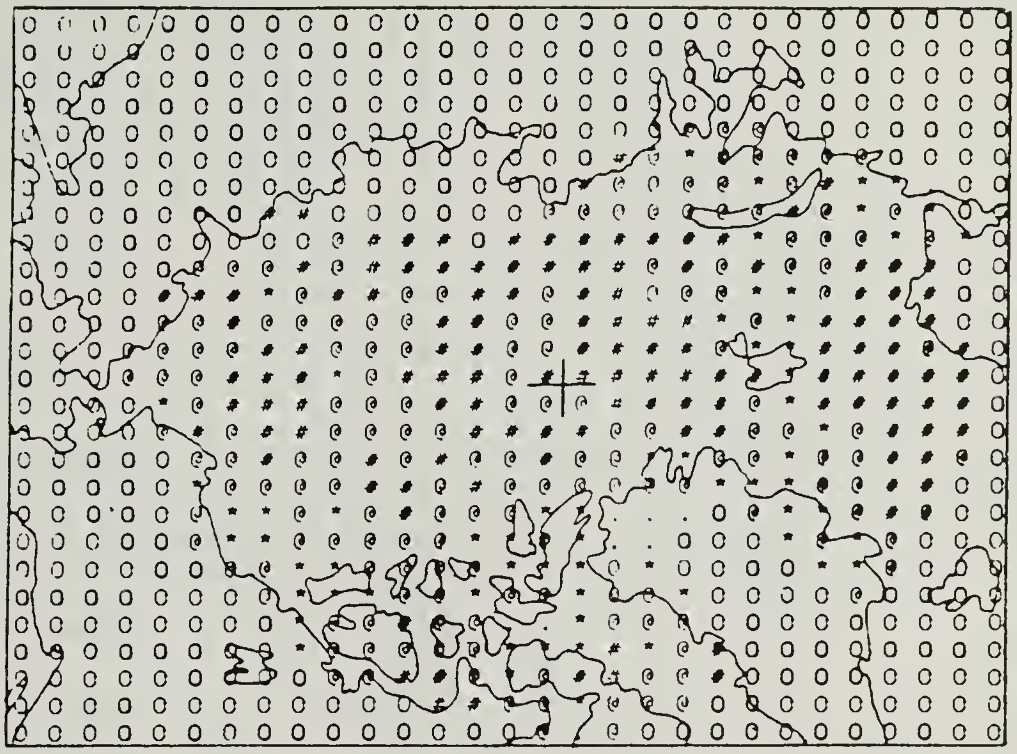
CLASSES 1+2


6/79

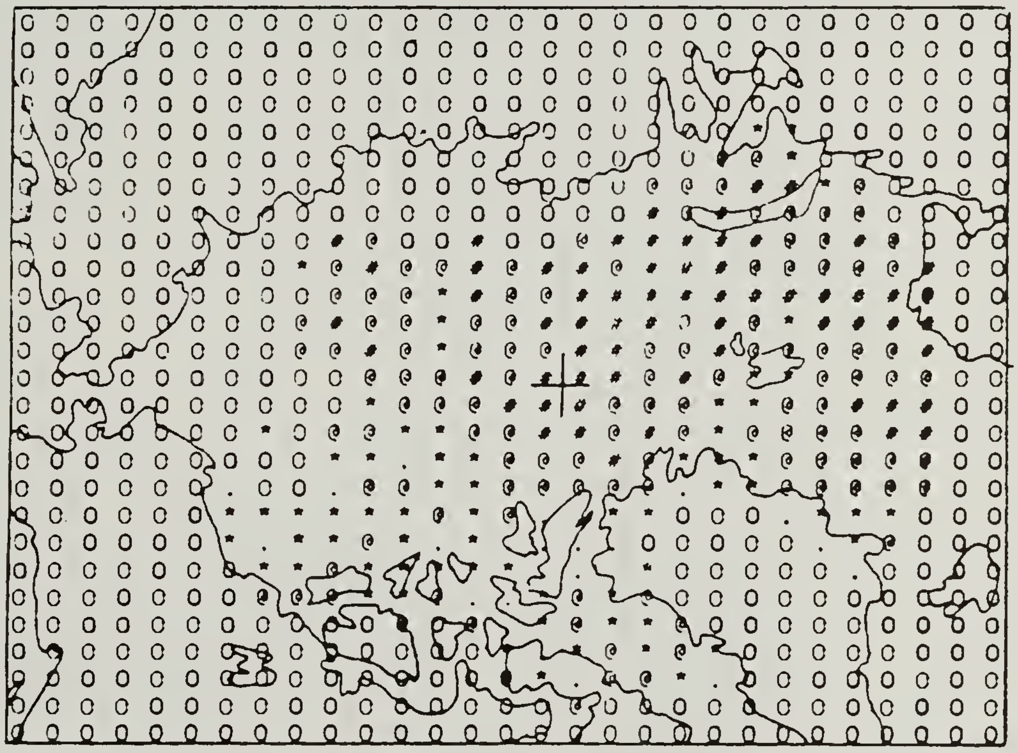

7/79


8/79

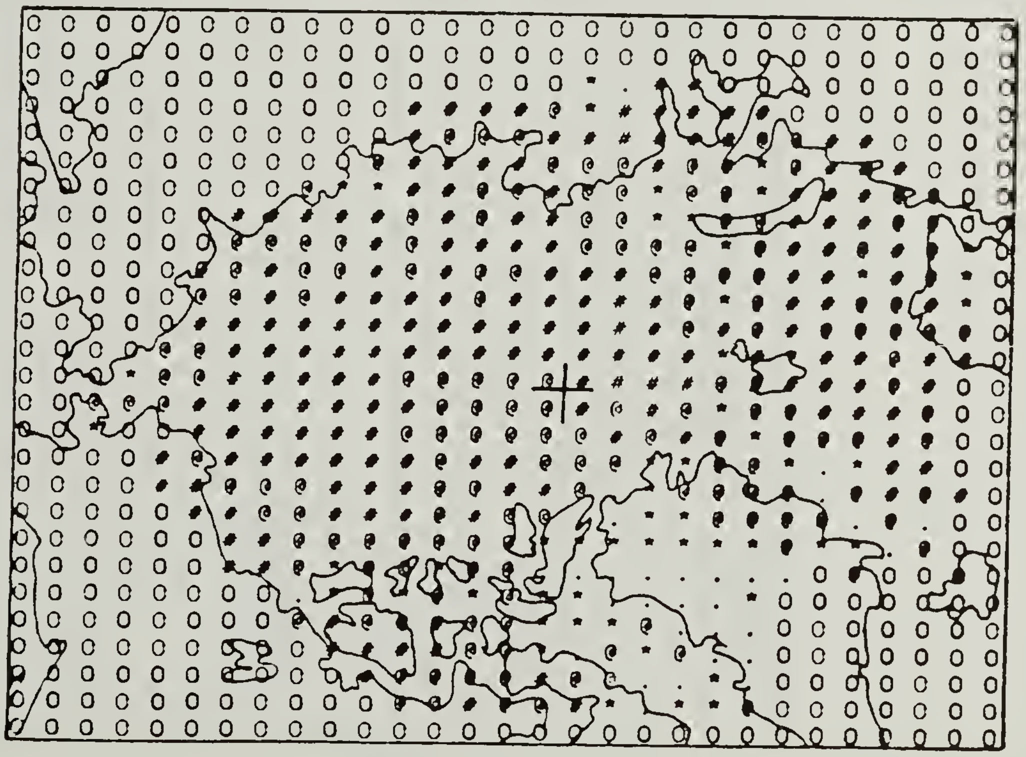
CLASSES 3+4



6/77

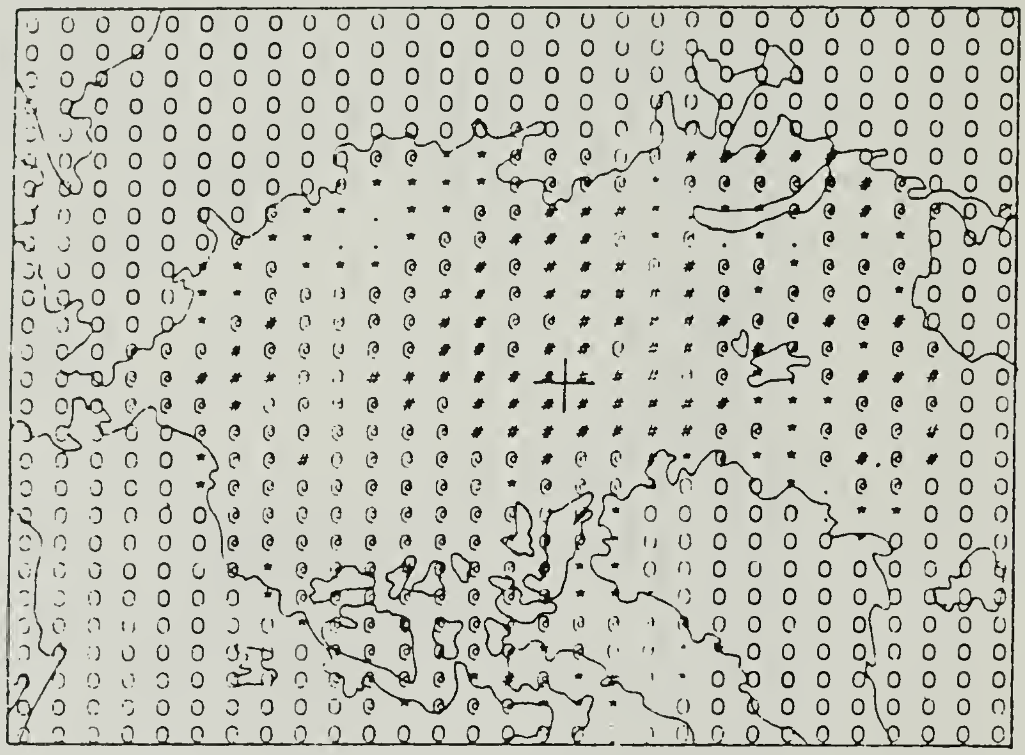


7/77

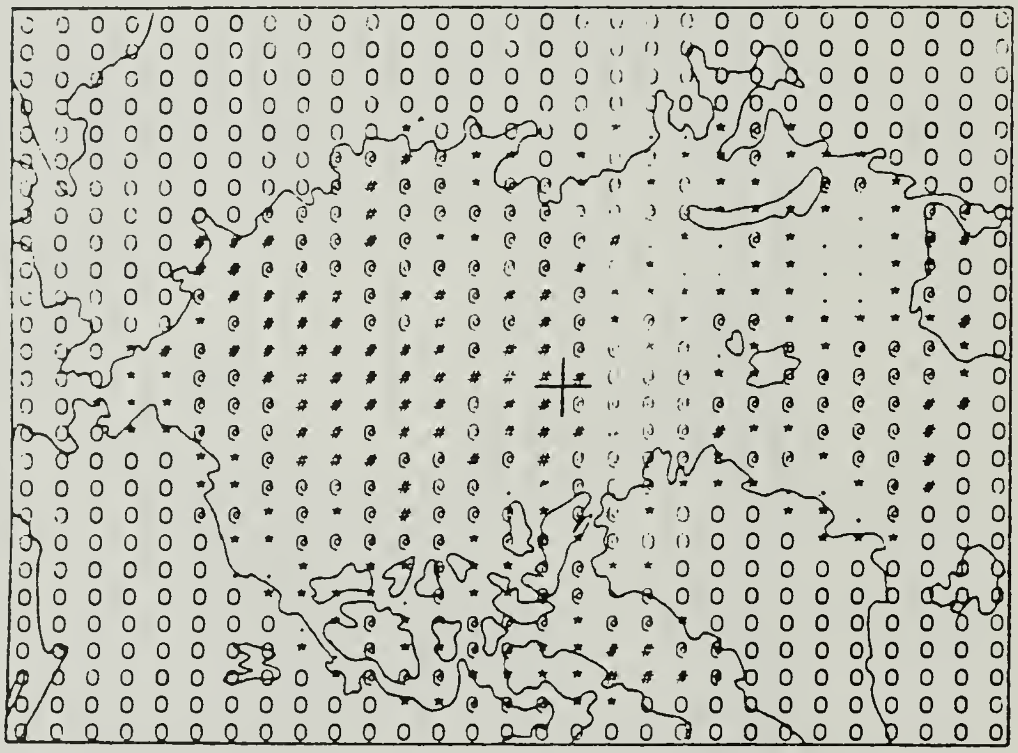


5/79

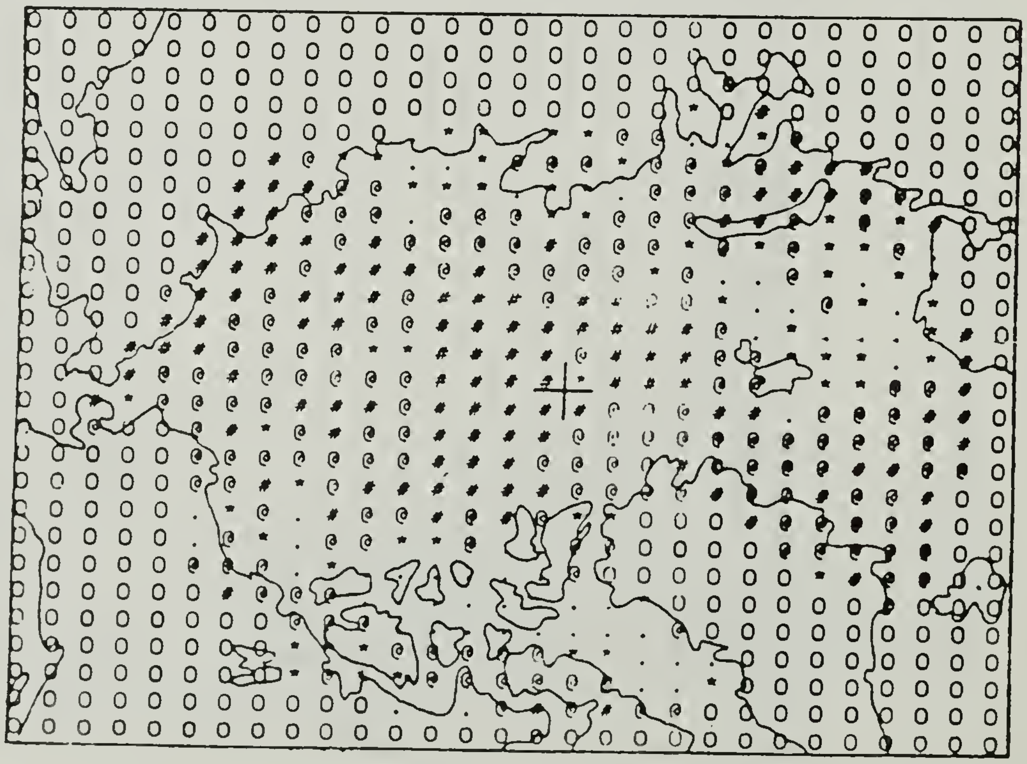
CLASSES 3+4



6/79



7/79



8/79

APPENDIX 6.

Cloud cover (top) and cloud top height (bottom) fields for the 15th of May, June, July and August 1977-1979. Cloud cover classes as in Appendix 2. Height classes are 1: cloud-free skies, 5: low clouds, 6: middle clouds, 7: high clouds. Missing data: 0. NMC grid cell numbers as in Appendix 2.

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51577

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51577

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 51579

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APPENDIX 7.

A. Daily (NMC 00Z) surface pressure fields over the Arctic Basin for cloud chart dates in June and July 1977 and May 15 - August 15, 1979. Add 900 mb to chart values >50 and 1000 mb for values <50. NMC grid cell numbers as in Appendix 2.

B. Estimated mean monthly surface pressure fields for June and July 1977 and May-August 1979 derived from digitized data in A. Isobars are marked as in A.

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60177

77  29898 2 2 2 6 6 6101010101014141822222222222222262626262626
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     6 6 2 2 6 6 6 6101010101014141416161616161616161622222222
     6 6 6 6 6 61010101010101010141414141414141414181818181818
    10 6 6 6 610101414141414101010101010101014141418181818181818
    101010101010141414181410 10 6 6 6 6 6 6101014141822221818 18
    10101010101414181818181410 6 6 2 2 2 6 6101414182222221818
    10101010101414181822181410 6 2989898 2 6 61014182222221818
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    2222101818181822262626262222181818141414141414101818141818
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60777

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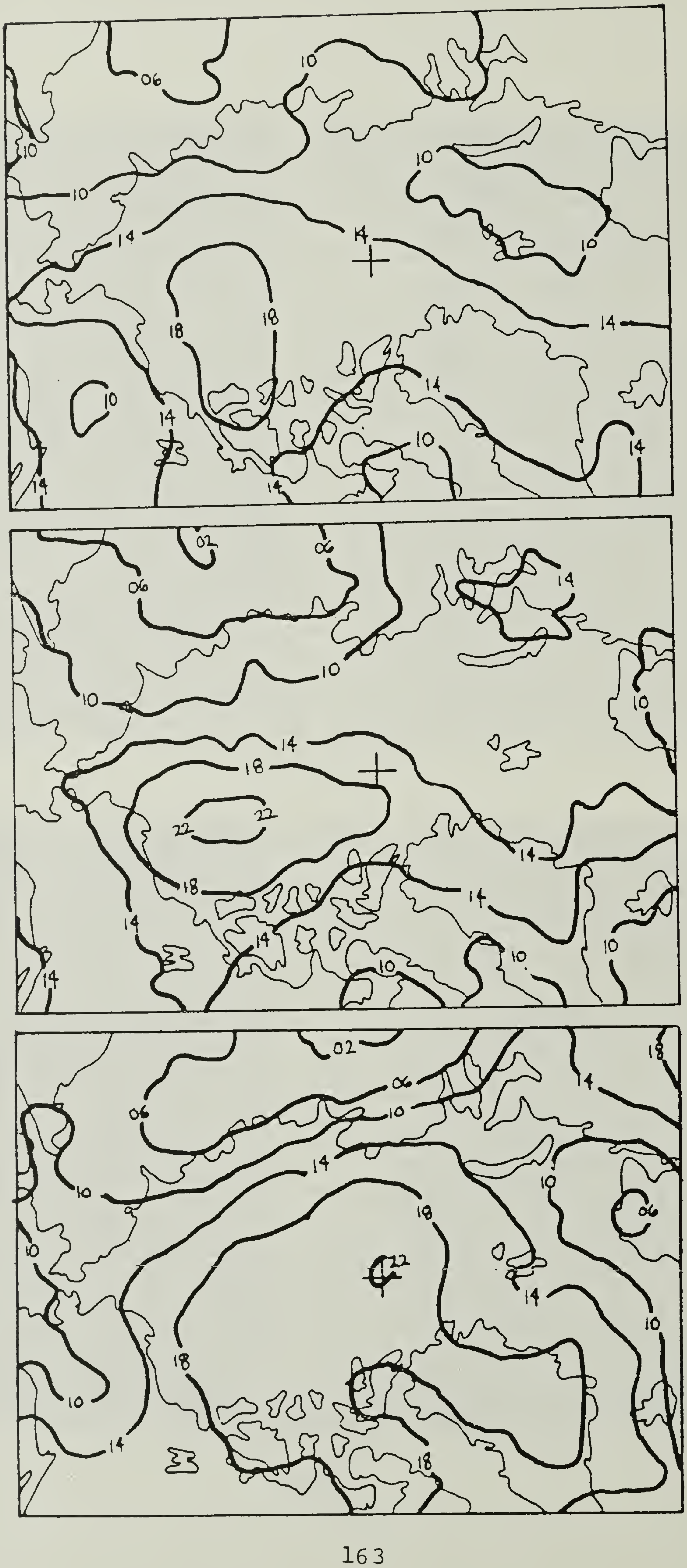
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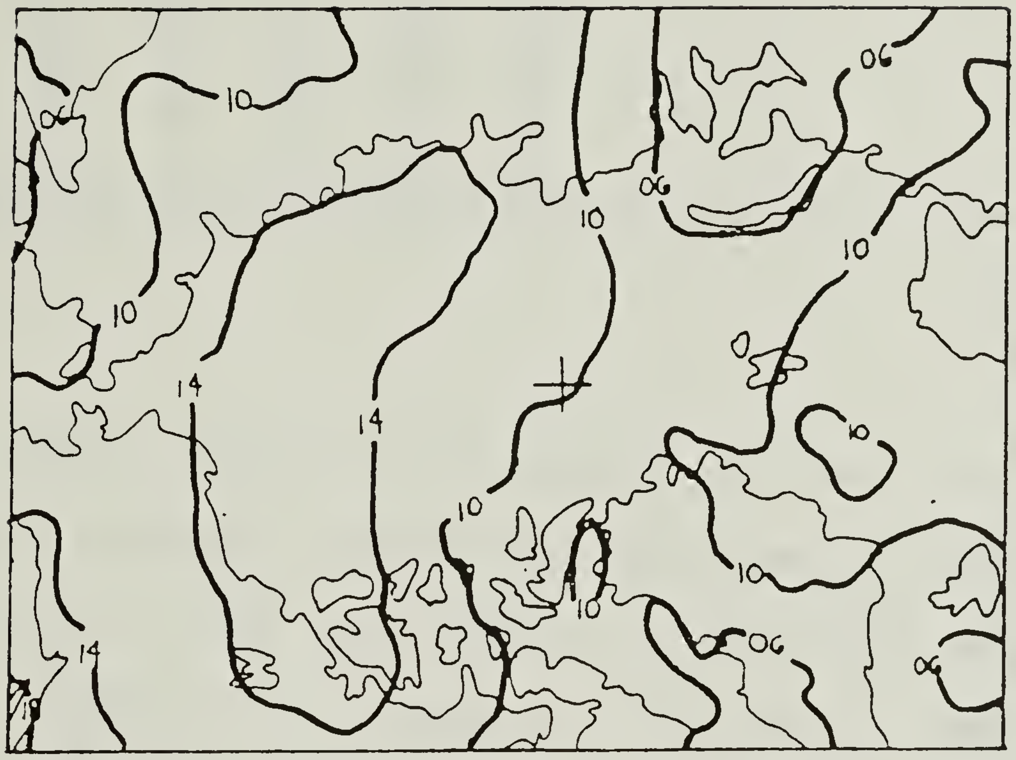

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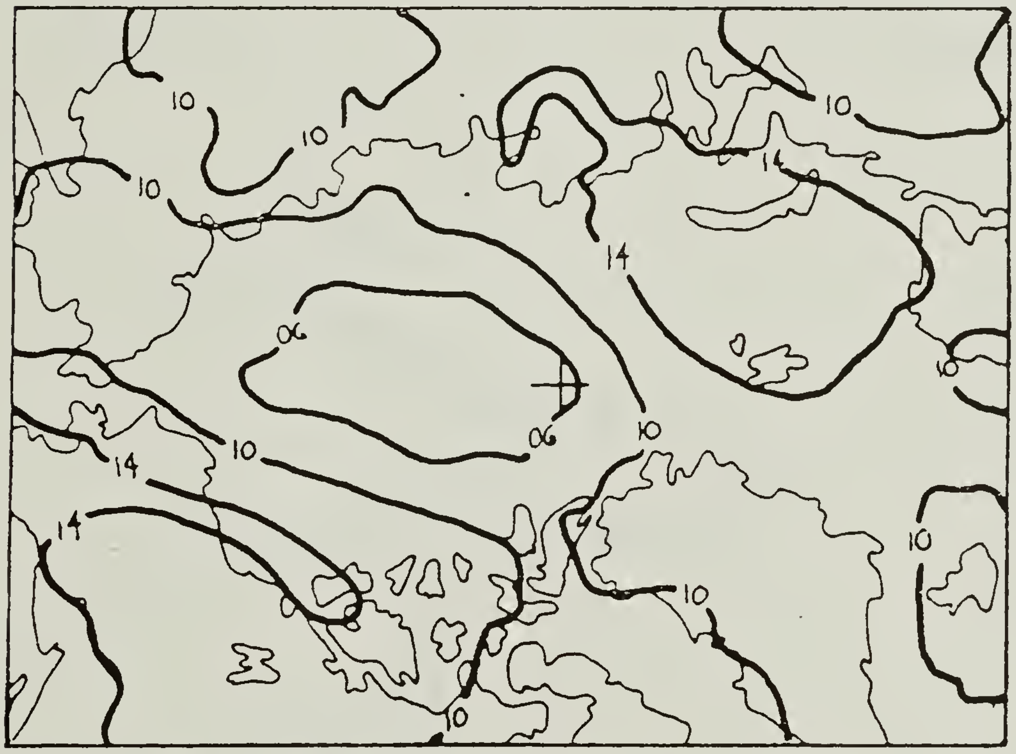

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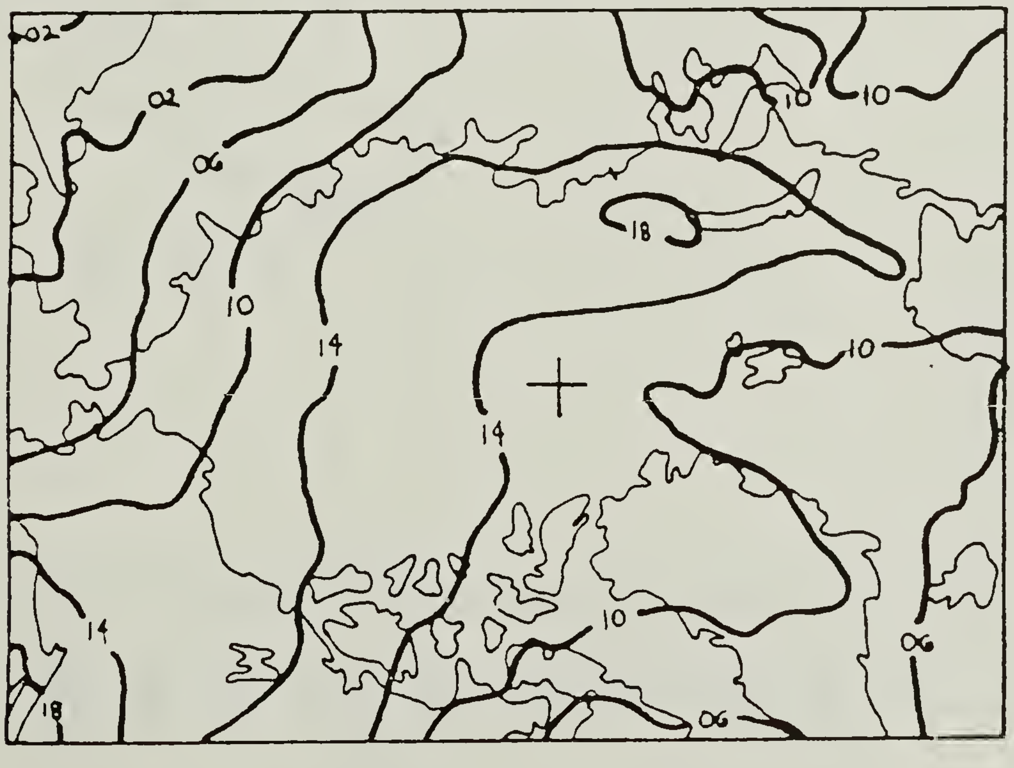

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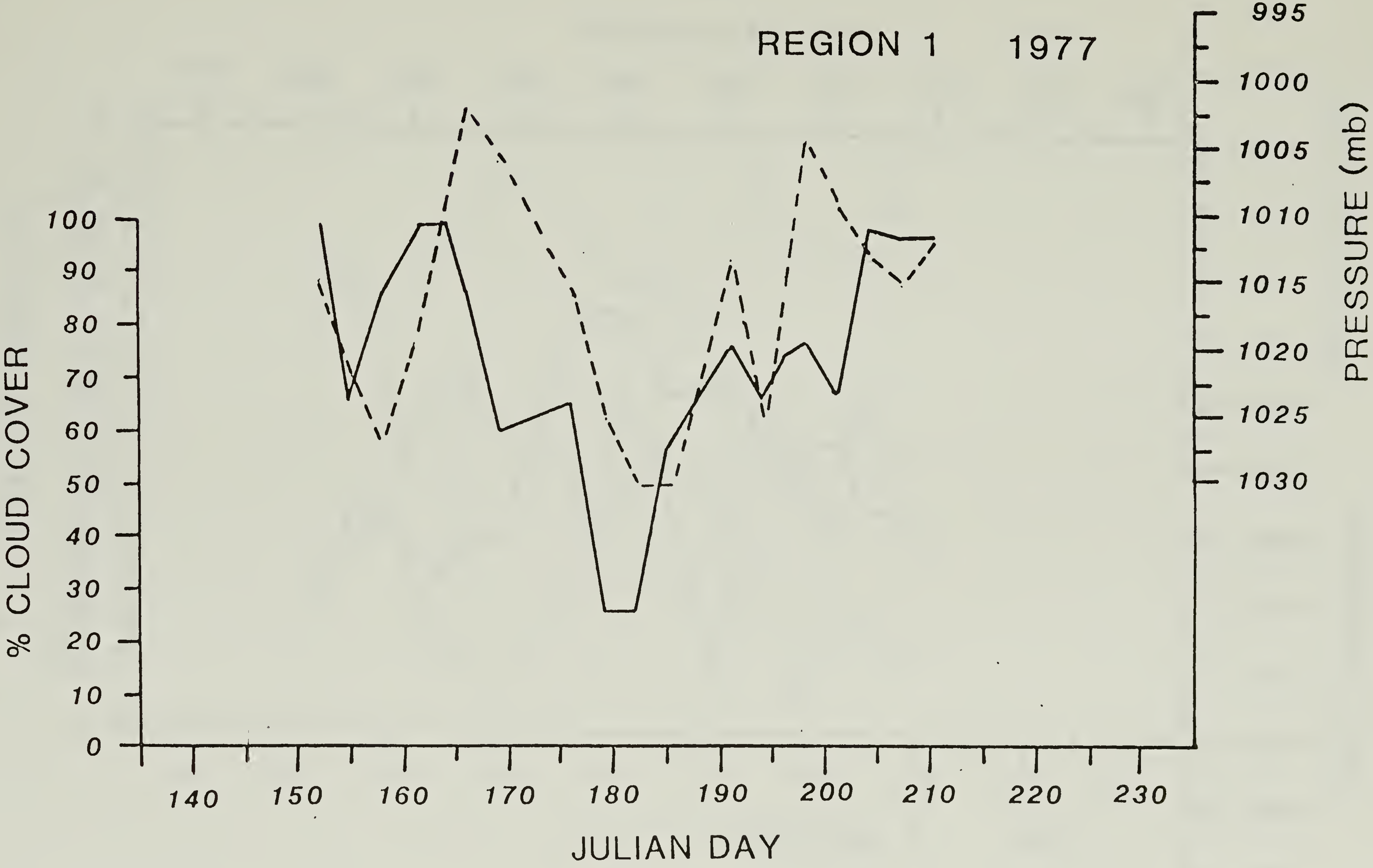
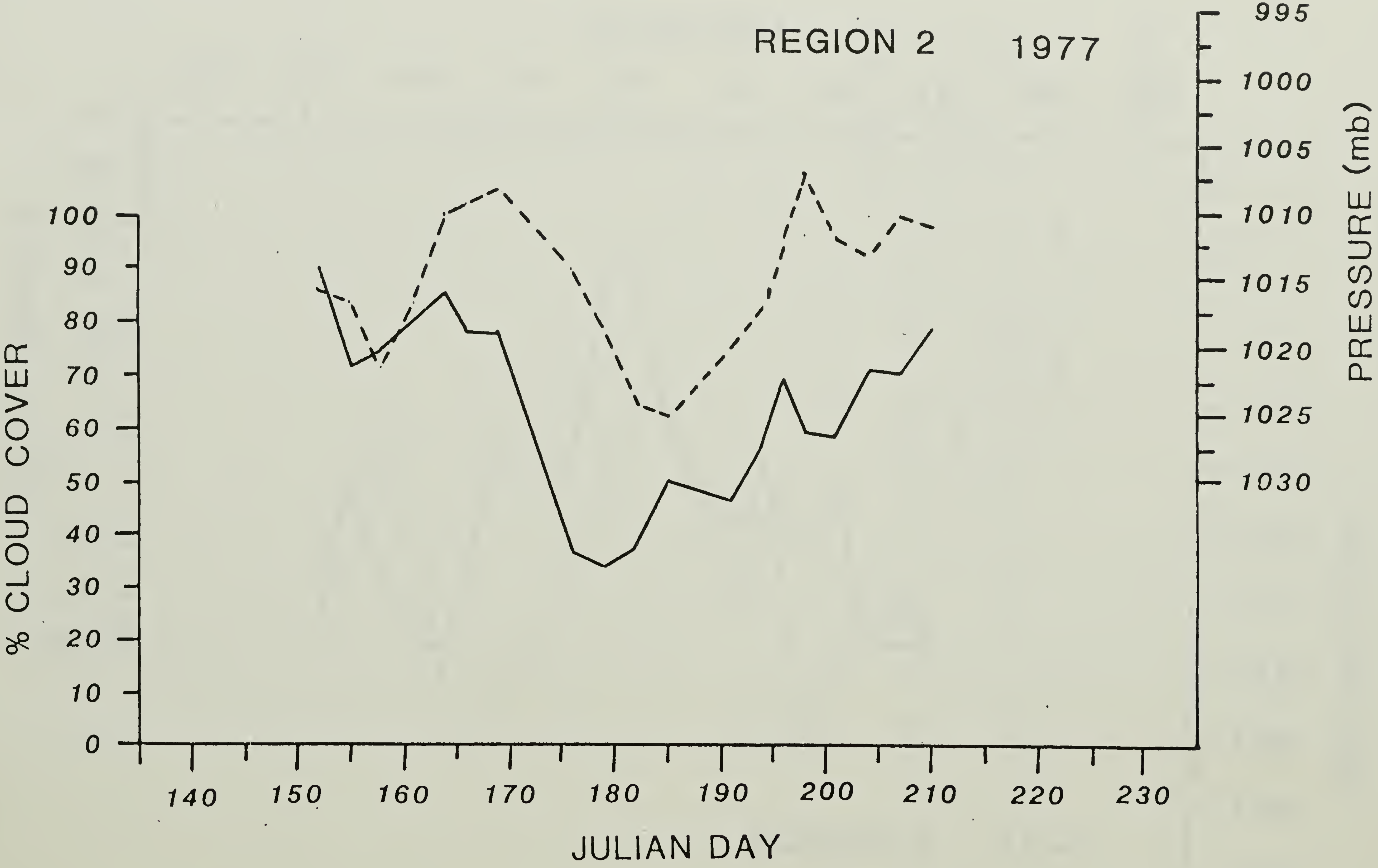
APPENDIX 8.

Percent cover of moderate and thick clouds (classes 3+4) (solid line) and mean NMC 00Z surface pressure (dashed line) on chart dates from June 1 (Julian Day 152) to July 29 (JD 210), 1977 and May 15 (JD 135) to August 15 (JD 227), 1979 in the 5 study regions.



REGION 1 1977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80
70
60
50
40
30
20
10
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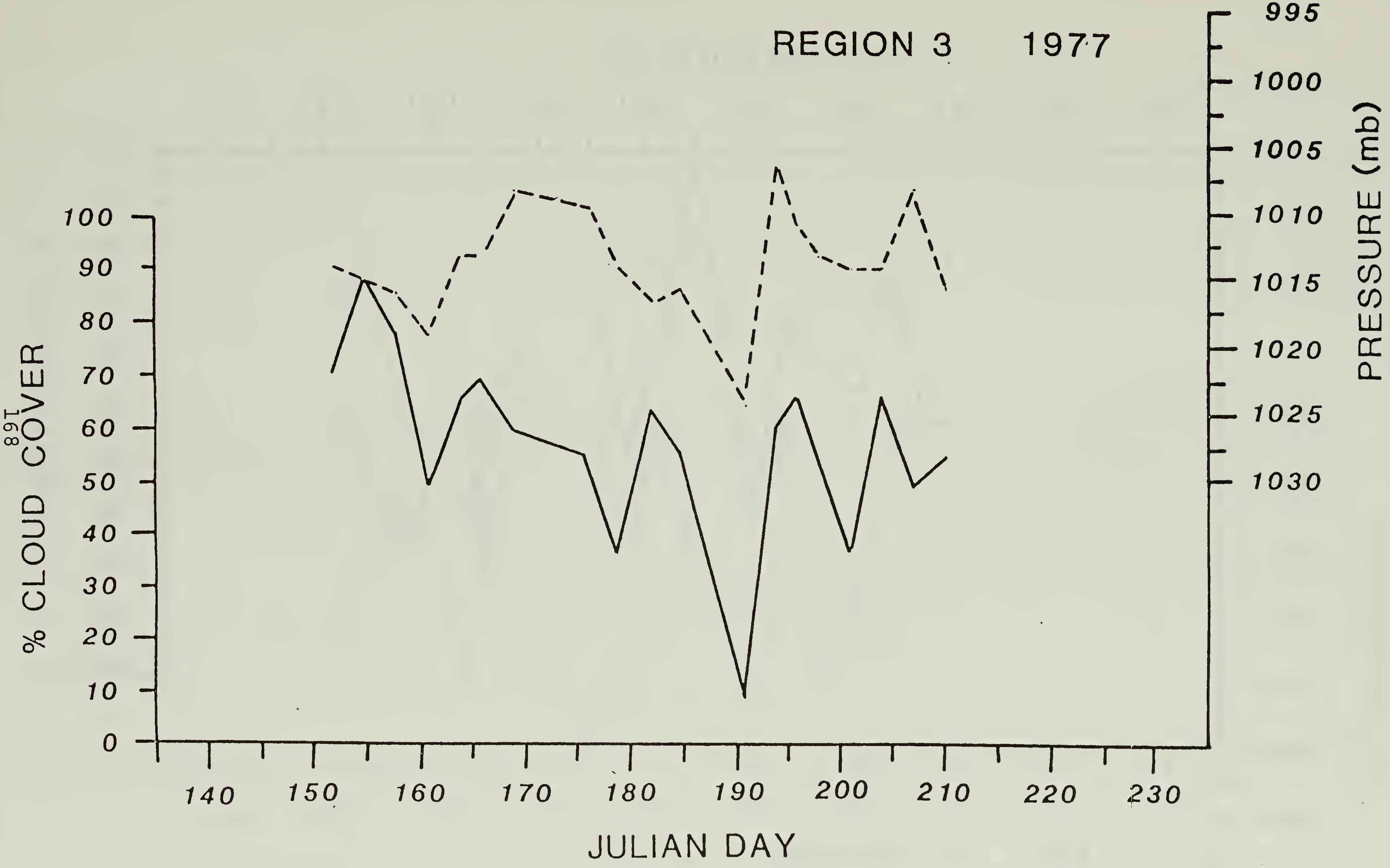
1005
1010
1015
1020
1025
1030
140
150
160
170
180
190
200
210
220
230
JULIAN DAY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% CLOUD COVER
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90
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40
30
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PRESSURE (mb)
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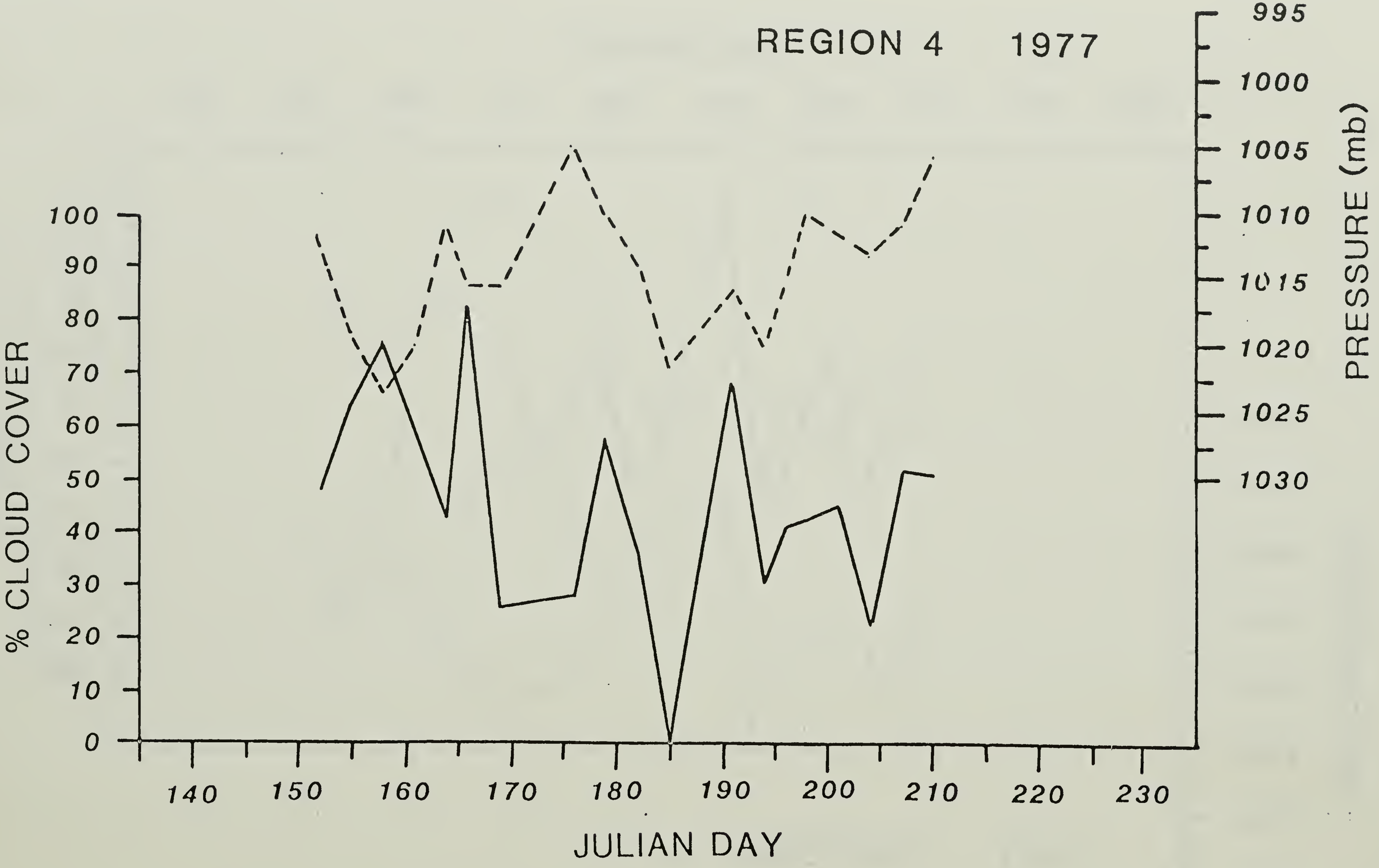
JULIAN DAY



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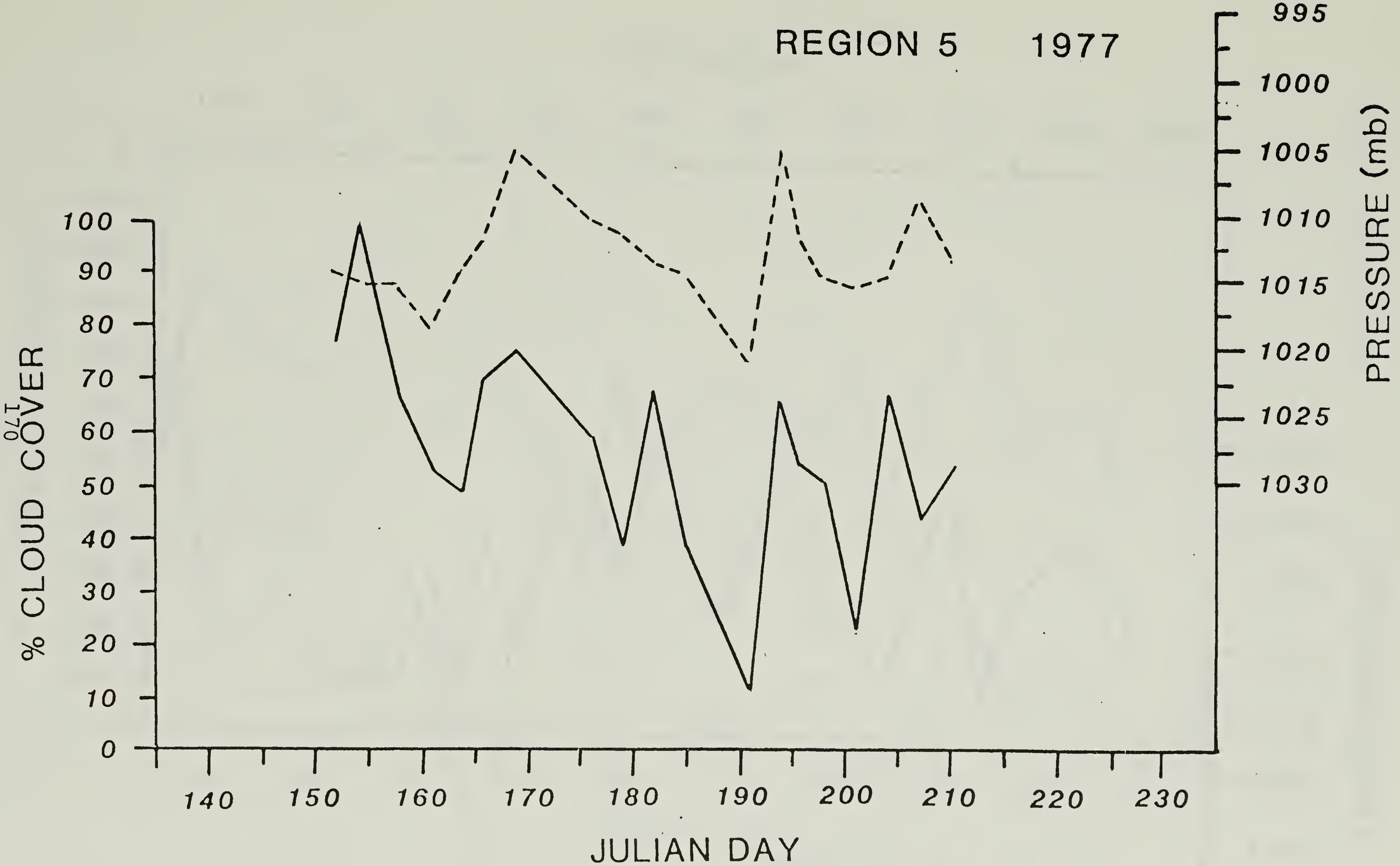
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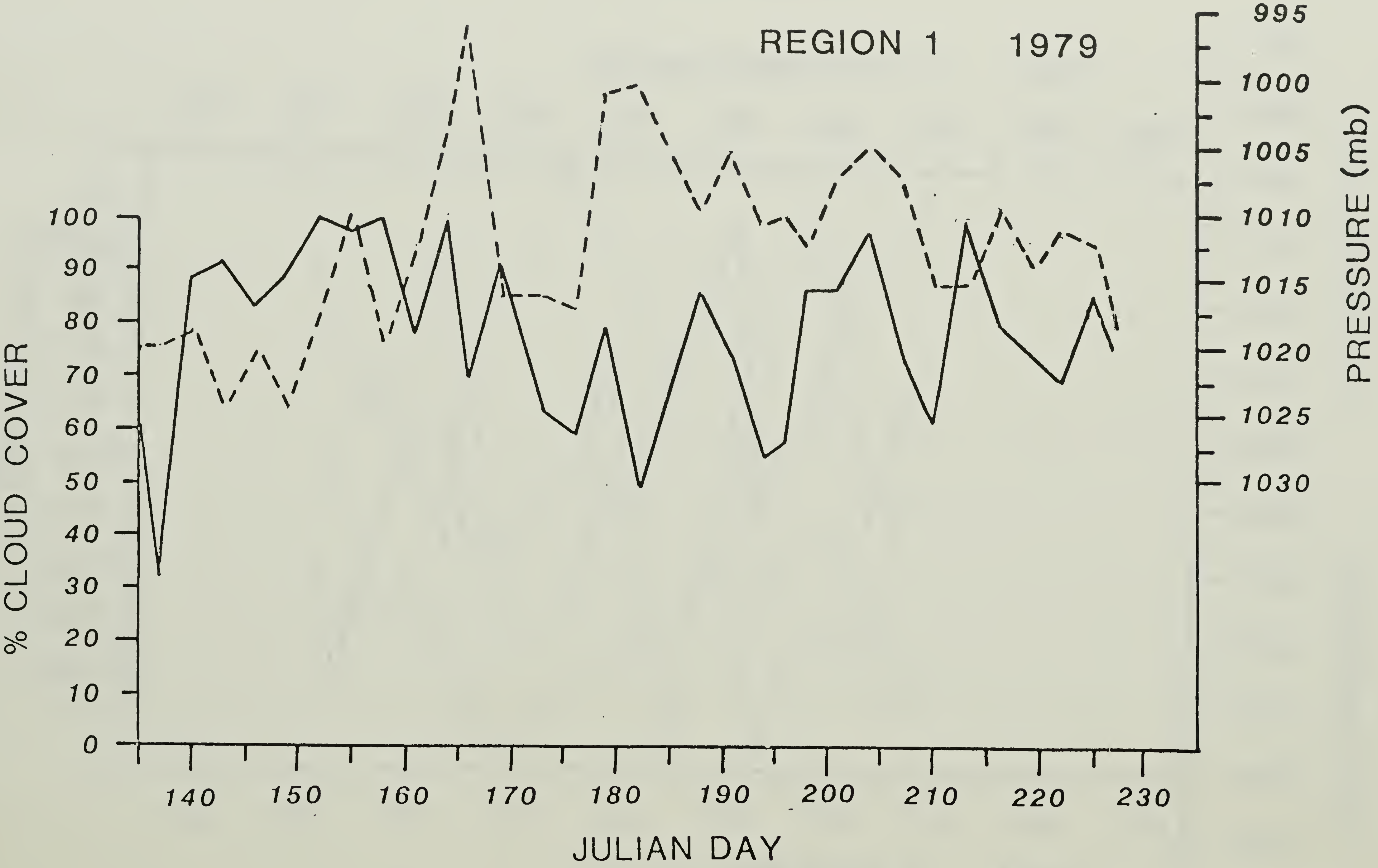
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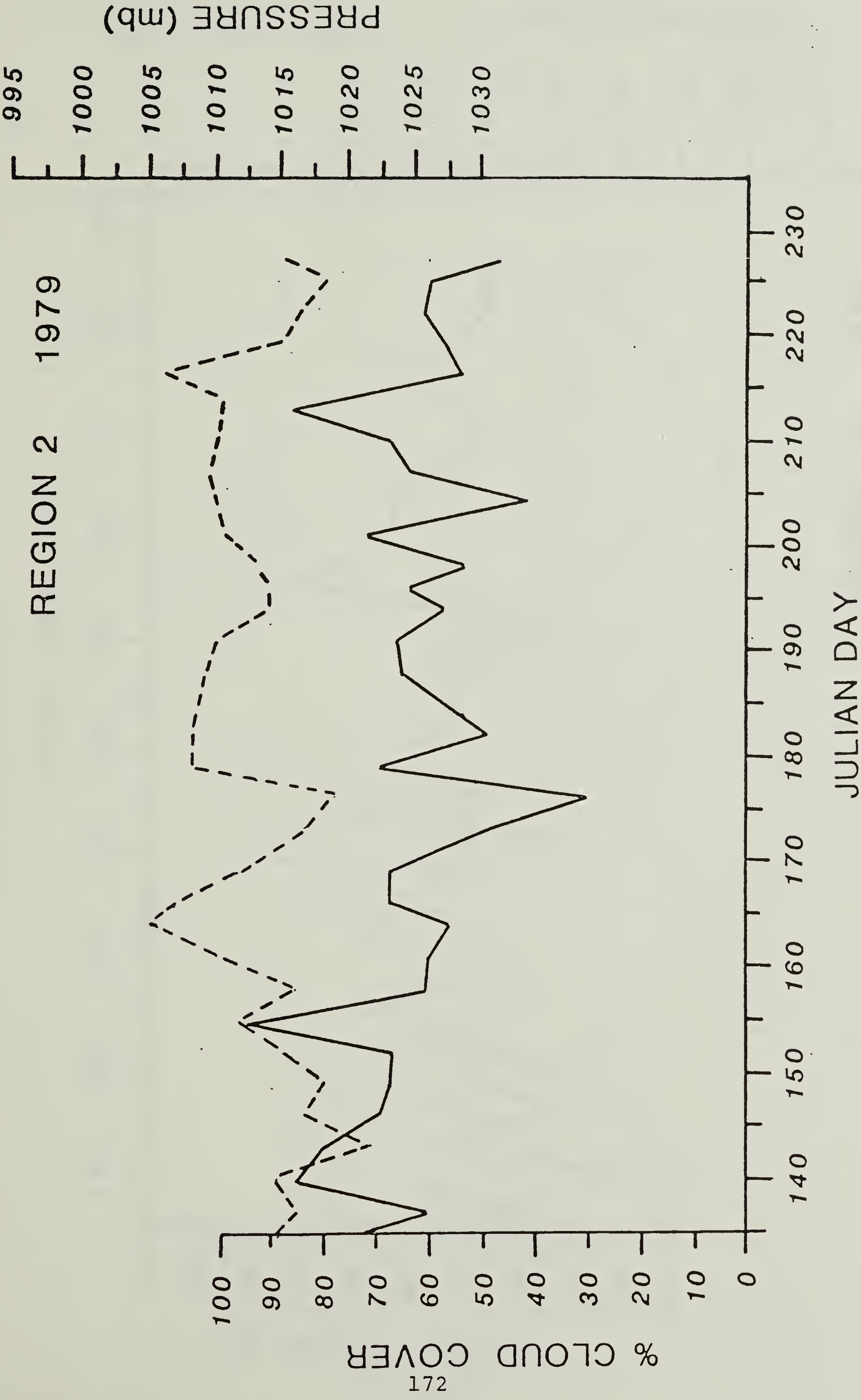
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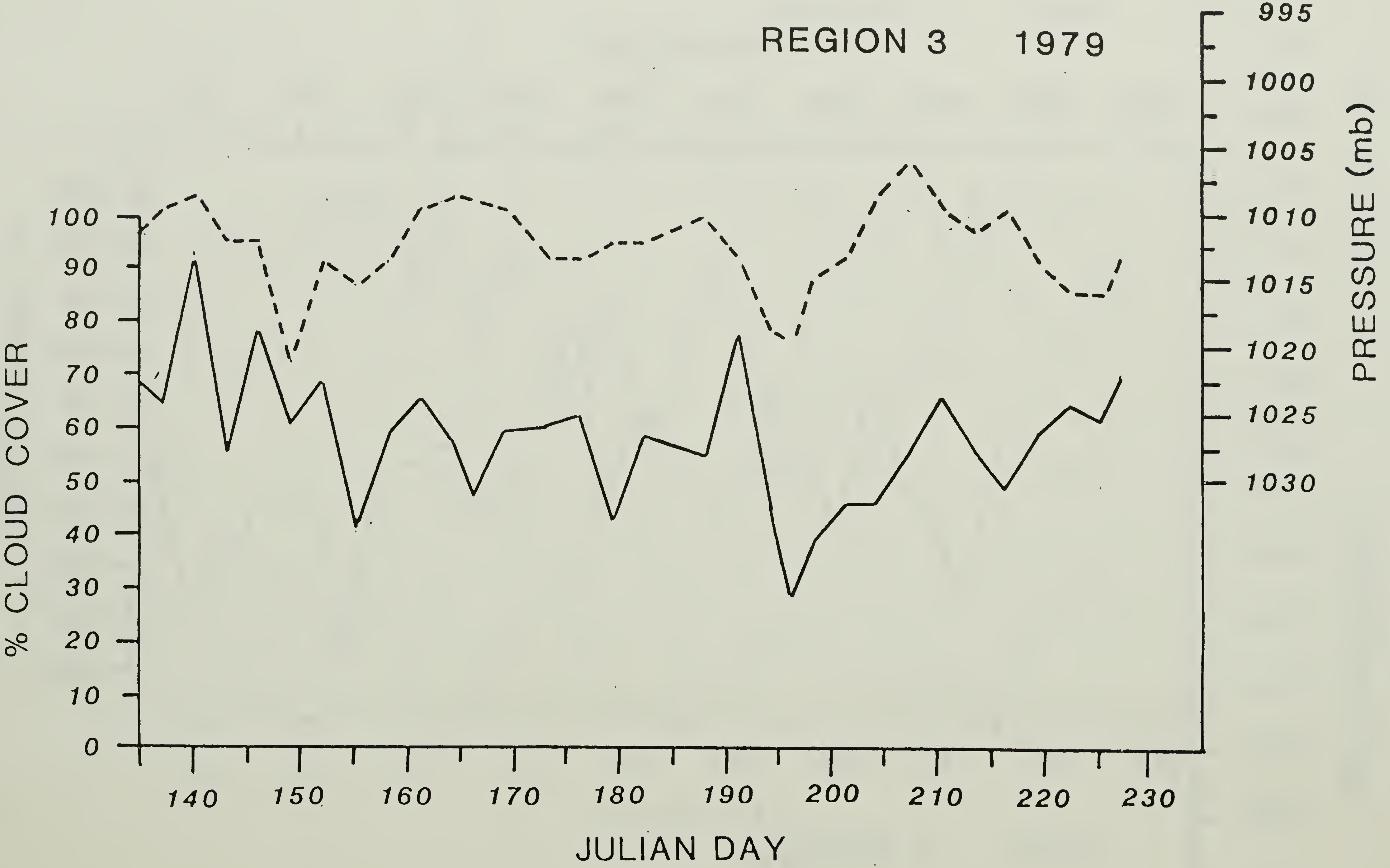
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JULIAN DAY
PRESSURE (mb)
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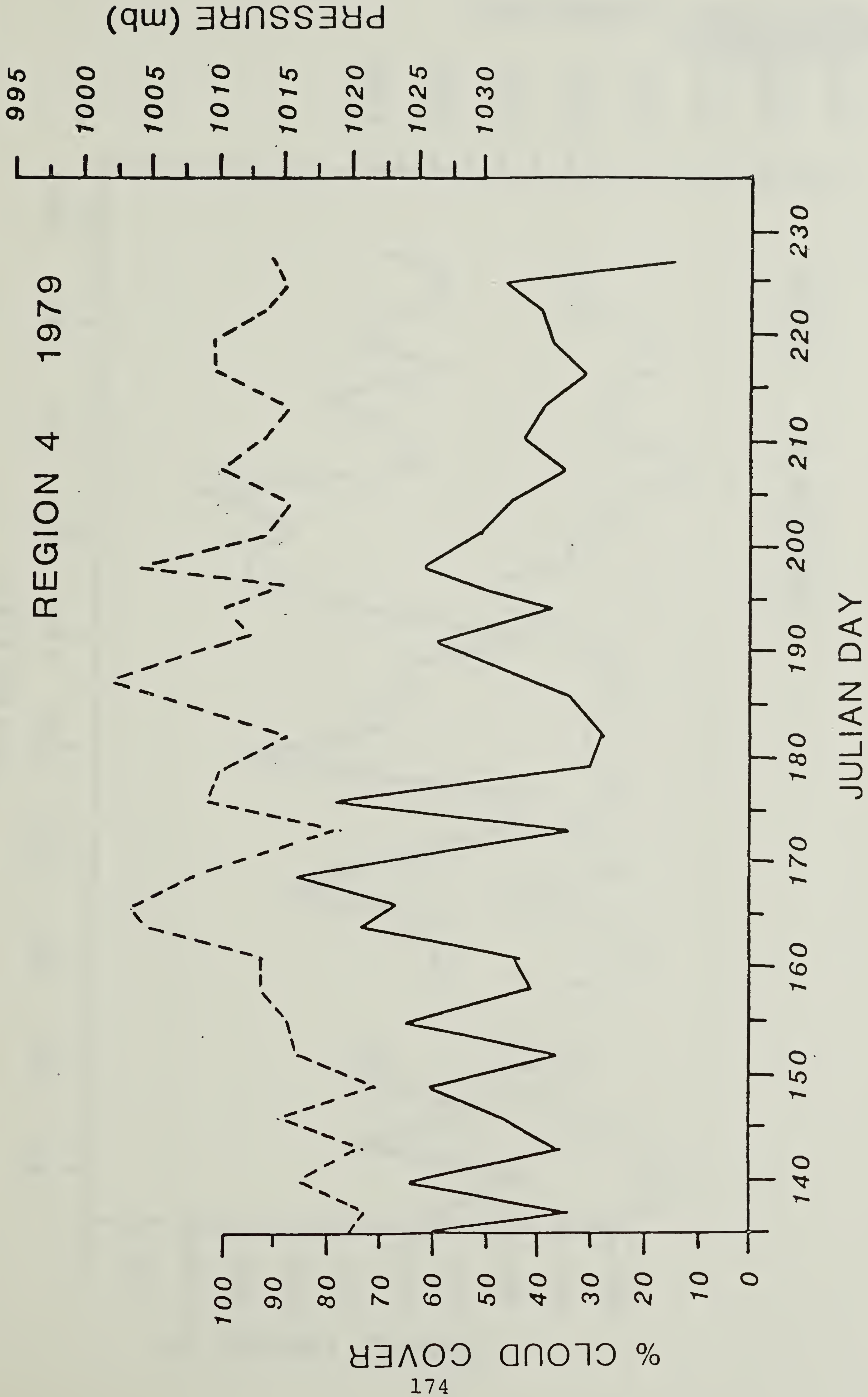
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PRESSURE (mb)
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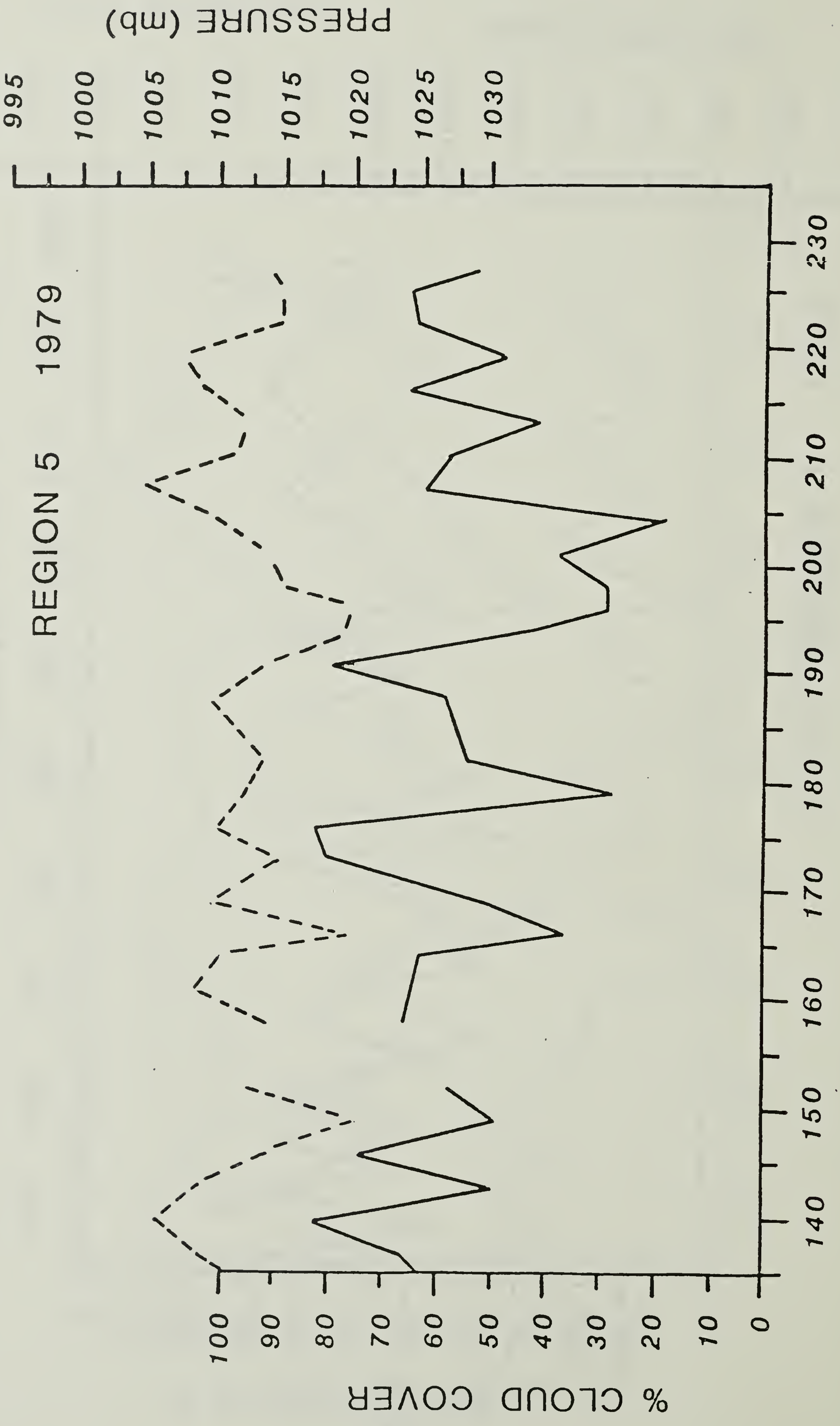
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